Modular Pebble-Bed AHTR Design Review

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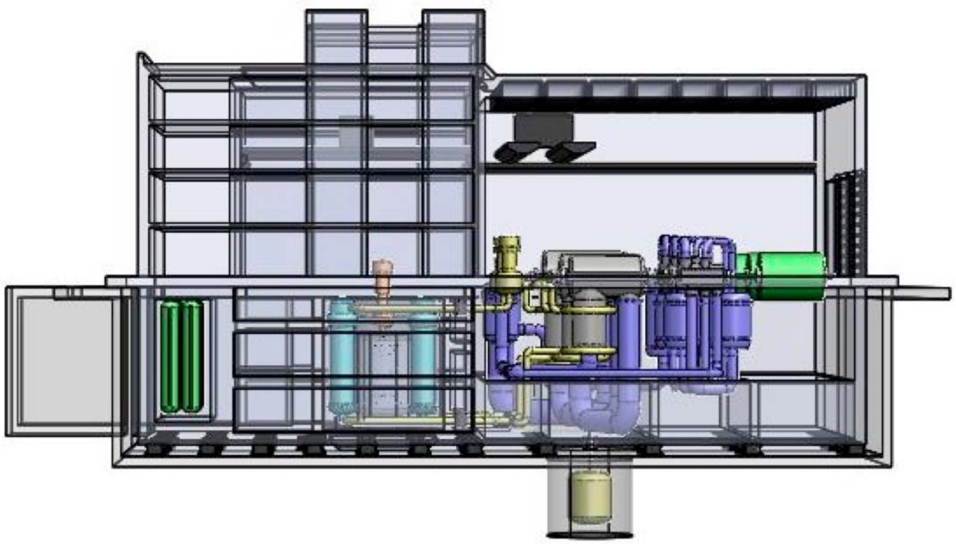
Design Status Update
October 7, 2009

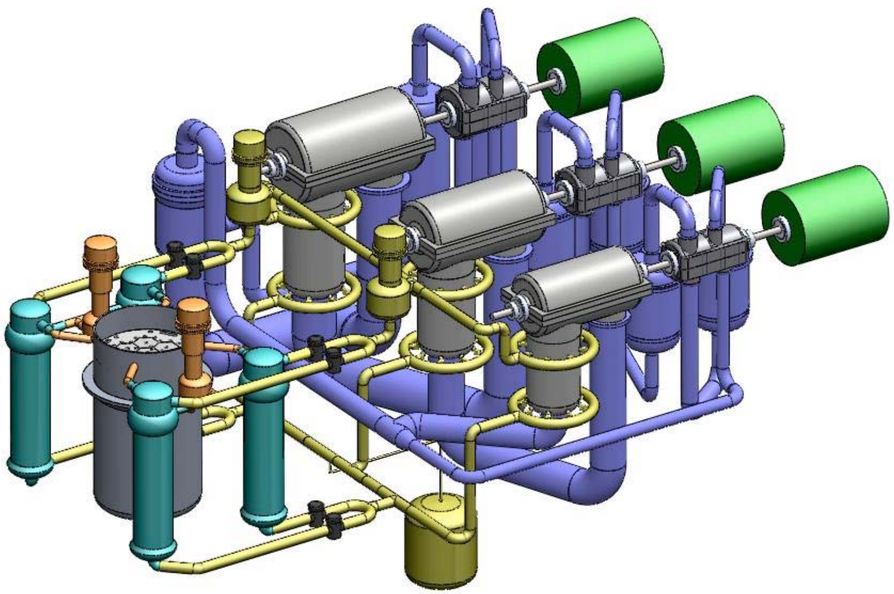


900 MWth, 410 MWe PB-AHTR

Overview

- **Modular PB-AHTR design overview**
  - **410 MWe, 900 MWth**
- **AHTR licensing framework**
- **AHTR development path**
  - **Design**
  - **Simulation and modeling**
  - **Experimental program**
- **Liquid Salt Component Test Facility (CTF)**
  - **High-level functional requirements**
  - **Existing experience base**
    - » **MSBR/HTGR/SFR/LWRs**
  - **New technologies**

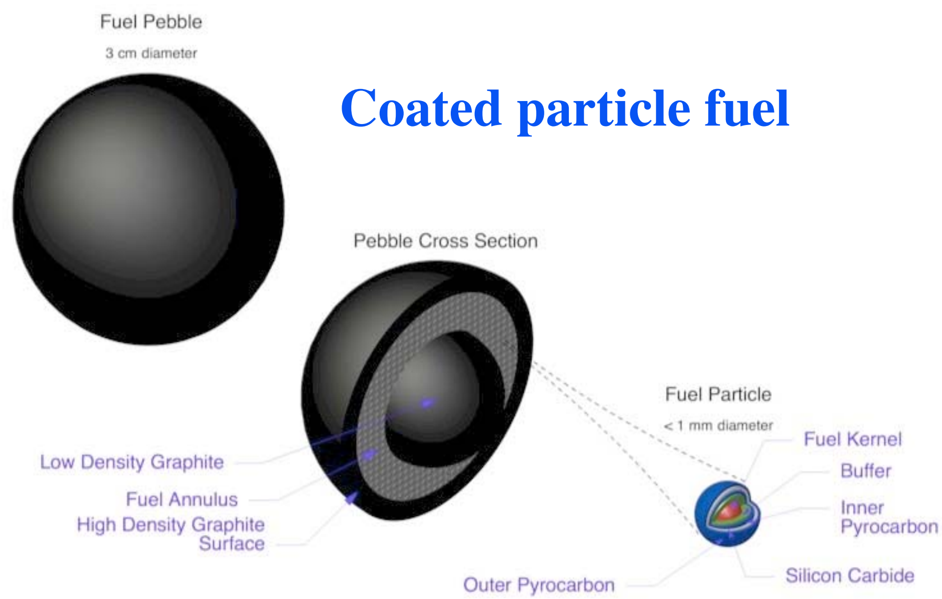
– **FHR-16 16-MWth test reactor**

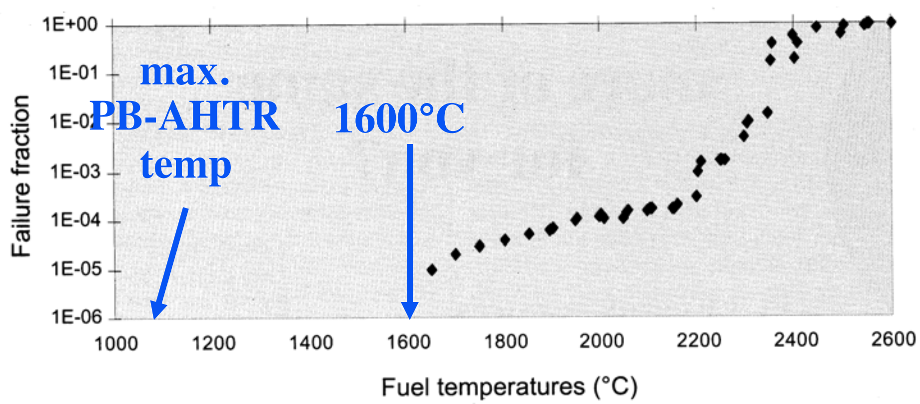


Advanced High Temperature Reactor (AHTR)
Technology Overview

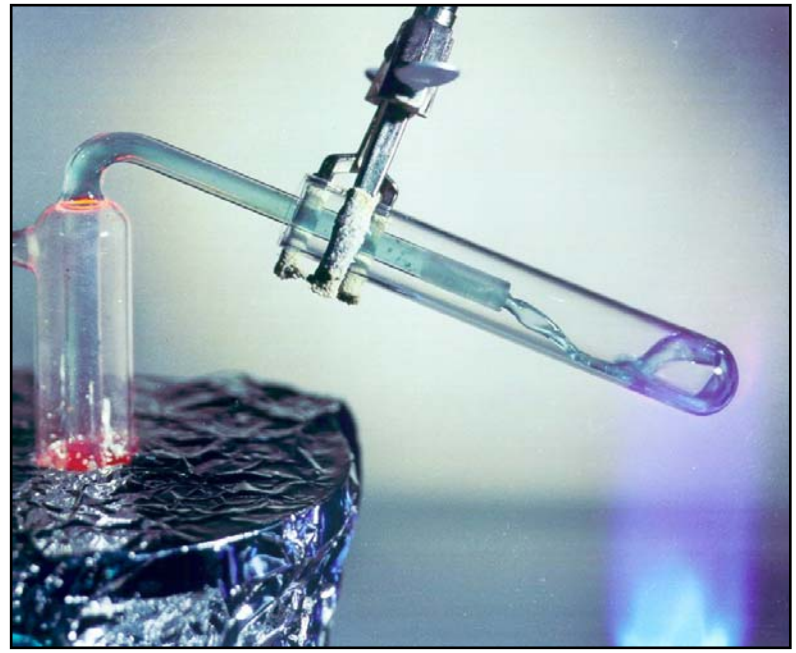
Advanced High Temperature Reactors (AHTRs) combine two older technologies

Coated particle fuel





Fuel performance chart (Source: PBMR [Pty] Ltd.)



Liquid fluoride salt coolants

Excellent heat transfer
Transparent, clean fluoride salt
Boiling point ~1400ºC
Reacts very slowly in air
No energy source to pressurize containment
But high freezing temperature (459°C)
And industrial safety required for Be

AHTRs have uniquely large fuel thermal margin

UC Berkeley

Liquid fluoride salts have fundamentally different properties than other reactor coolants

Thermophysical Properties* of S-PRISM, GT-MHR, and AHTR Reactor Coolants and Materials

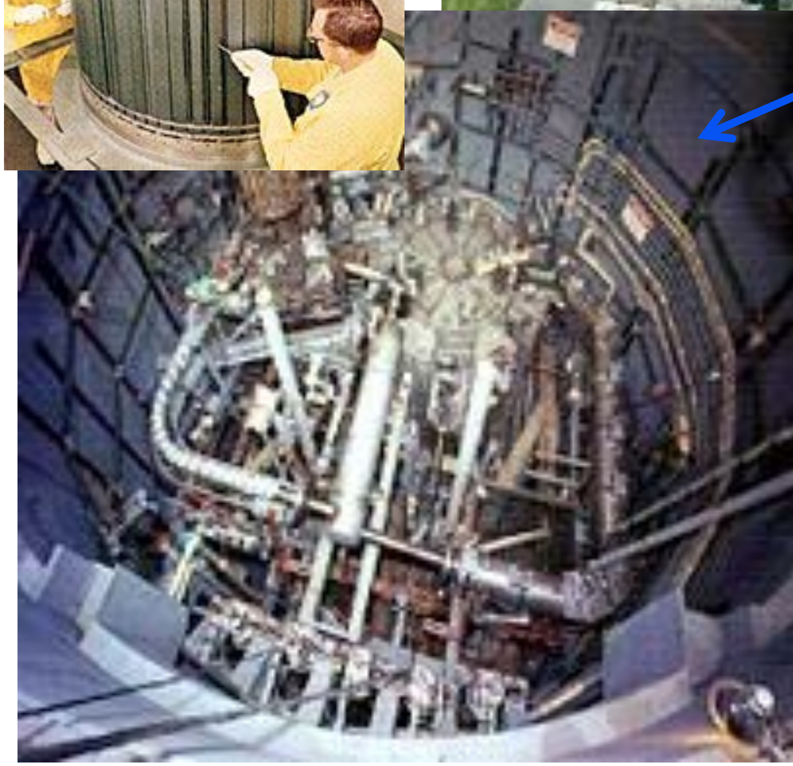
Material	T_{melt} (°C)	T_{boil} (°C)	ρ (kg/m^3)	C_p (kJ/kg°C)	ρC_p (kJ/m^3°C)	k (W/m°C)	$\nu \cdot 10^6$ (m^2/s)
$^7Li_2BeF_4$ (Flibe)	459	1430	1940	2.34	4540	1.0	2.9
$0.58NaF\text{-}0.42ZrF_4$	500	1290	3140	1.17	3670	~1	0.53
Sodium	97.8	883	790	1.27	1000	62	0.25
Lead	328	1750	10 540	0.16	1700	16	0.13
Helium (7.5 MPa)			3.8	5.2	20	0.29	11.0
Water (7.5 MPa)	0	100	732	5.5	4040	0.56	0.13
Hastalloy C-276	~1350		8890	0.43	3820	9.8	
Graphite			1700	1.90	3230	200	

*Approximate physical properties 700°C except the pressurized water data shown at 290°C for comparison; ρ = density, C_p = specific heat, k = thermal conductivity, ν = viscosity.

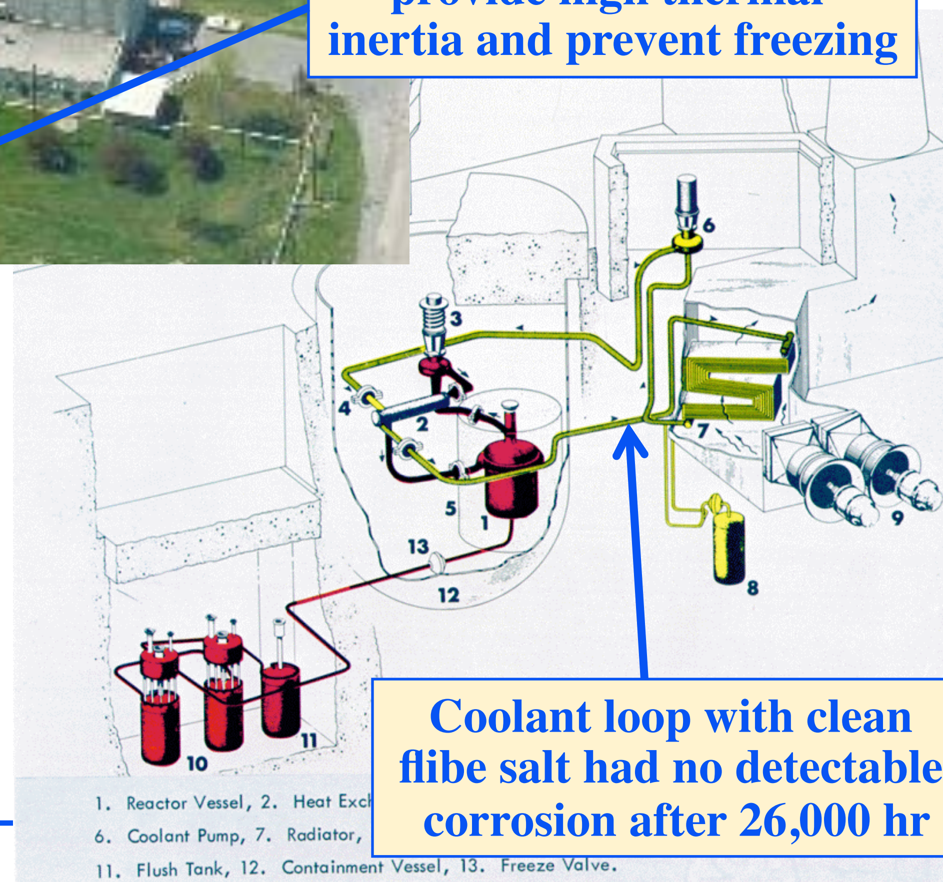
- **High volumetric heat capacity provides high thermal inertia**
  - **High power density, low pressure operation possible compared to helium cooled reactors**
  - **High efficiency, compact primary loop equipment compared to water cooled reactors**
  - **Transparent coolant, low thermal shock, low chemical reactivity compared to sodium cooled reactors**
  - **But high freezing temperature still requires safety systems to prevent and control slowly evolving overcooling transients**

The 8-MWth MSRE (1965-69) provided experience relevant to the development of an AHTR Test Reactor

Reactor cavity acted as an insulated furnace to provide high thermal inertia and prevent freezing



MSRE Systems and Components Performance, Oak Ridge National Laboratory, ORNL-TM- 3039, June 1973.



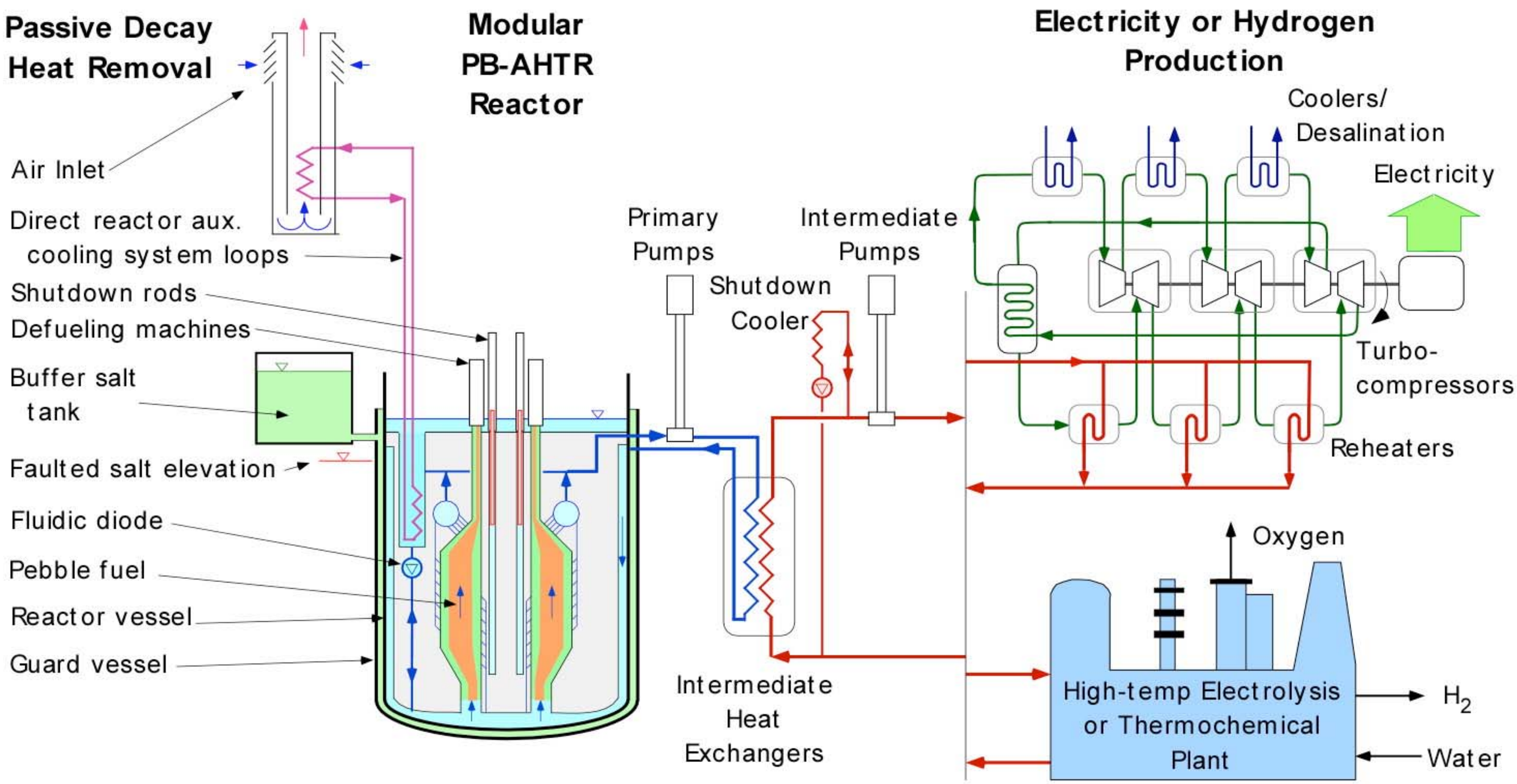
Coolant loop with clean flibe salt had no detectable corrosion after 26,000 hr

MSRE coolant salt loop showed negligible corrosion after 4 years of operation

- **Coolant salt loop contained clean Li_2BeF_4 salt (like PB-AHTR)**
  - **Operated for 26,000 hours at 550 to 650°C**
  - **Forced circulation operation to transfer heat from IHX to air-cooled radiator heat exchanger**
  - **Salt transferred to drain tank when not in operation**
- **Chromium content of coolant salt did not change measurably during this time**
  - **No detectable corrosion from coolant salt**
  - **Fuel salt CrF_2 content increase indicated ~4 mil total corrosion during 4 years operation**
  - **Fuel salt surfaces also showed significant intergranular cracking attributed to diffusion of the fission product tellurium**
- **After shutdown, examination of samples showed that no chromium depletion could be detected by metallographic methods.**

"The Development Status of Molten-Salt Breeder Reactors," ORNL-4812, pp. 200-201, pp.207-211, August 1972.

The UCB Modular PB-AHTR is a compact pool-type reactor with passive decay heat removal



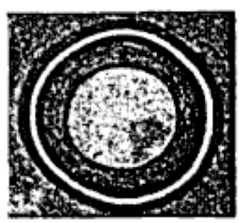
PB-AHTR fuel and materials

- **TRISO based pebble fuel**
  - Peak temperature during normal operation and accidents < 1000°C
  - Uses special pebble design operating at high power density (seed pebbles can reach full discharge burn up in < 1yr)
  - Requires confirmatory irradiation testing
- **Metallic components with clad construction**
  - Current baseline is Alloy 800H (ASME Section III code qualified to 760°C) with Hastelloy N † (or nickel?) clad, but further study needed
  - Molybdenum may be attractive for some reactor internals such as a core support shroud
    - » Thermal expansion coefficient matching graphite
    - » New technologies to manufacture/fabricate?
- **Reflectors are graphite**
  - Compatibility with fluoride salts excellent but surface treatment methods should be checked
  - Recent scoping experiment shows that fluoride salt can be an excellent lubricant for graphite pebbles sliding on graphite
- **Carbon composite structures could also be valuable**
  - e.g., shut-down rod channel liners)

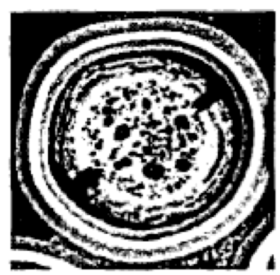
† Hastelloy N modified with 2% titanium shows excellent corrosion and neutron embrittlement resistance, "The Development Status of Molten-Salt Breeder Reactors," ORNL-4812, pp. 205, August 1972.

PB-AHTRs maintain uniquely large thermal margins for damage to fuel

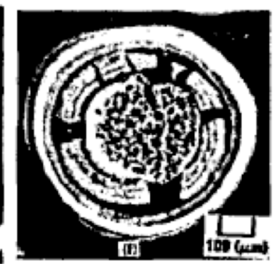
- **Among Gen IV reactors, PB-AHTR has a uniquely large thermal margin (100's of degrees) to fuel damage temperatures under all transients and accidents**
- **Particles operate below 1100°C threshold for radio-silver diffusion**
- **Air/steam ingress and chemical attack are impossible**
- **Coolant temperature limit is established by thermal limits on primary loop metallic structures**
- **Core power density limit established by fuel particle power limits**
  - **Threshold for significant cracking of buffer layer is ~300 mW**



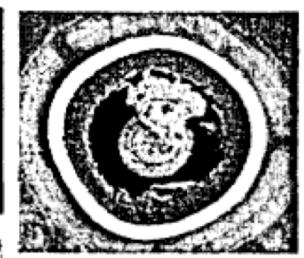
Intact Buffer



Cracked Buffer



Severe Cracking



Significant Shrinkage

R.N. Morris, D.A. Petti, D.A. Powers, B.E. Boyack, , "TRISO-Coated Particle Fuel Phenomenon Identification and Ranking Tables (PIRTs) for Fission Product Transport Due to Manufacturing, Operations, and Accidents, NUREG/CR-6844, Vol. 1,pg. 3-11, 2004.

In September 2007 UCB published 3 key papers on the Pebble Bed AHTR

- **Neutronics analysis, verifying that the UCB PB-AHTR**
  - **can be designed with negative void reactivity**
  - **can achieve high discharge burn up, comparable to MHRs**
- **Thermal hydraulic analysis, using RELAP5-3D to verify that the PB-ATHR**
  - **has gentle response to Loss of Forced Cooling Transient**
  - **can be designed to have acceptable response to Anticipated Transient Without Scram**
  - **Power levels up to 4800 MWth possible**
- **Results from the Pebble Recirculation Experiment (PREX-1), verifying**
  - **pebble injection into the reactor cold leg**
  - **lower plenum pebble landing dynamics**
  - **pebble defueling from the top of the reactor core**

PREX-1 with 8300 pebbles

LEU-fueled AHTRs consume less uranium than LWRs and PBMRs

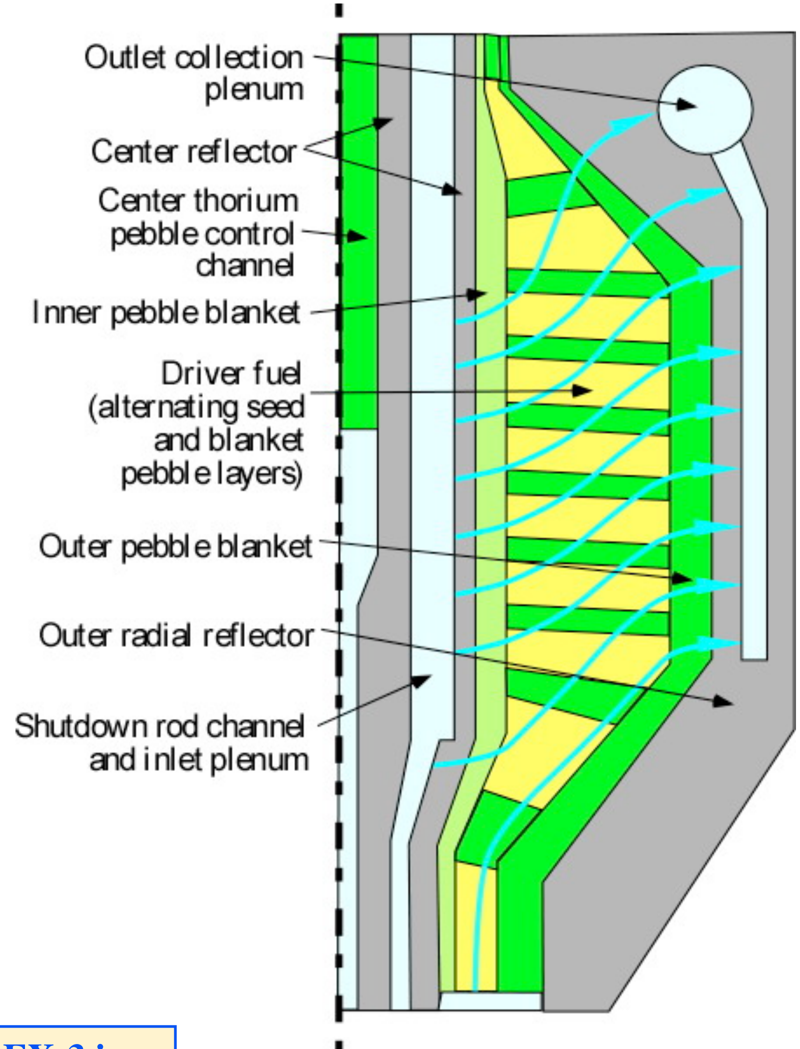
Parameter	LWR	Integral PB-AHTR	PBMR
Discharge burn up (MWt-day/kg)	55	117	80
Fuel enrichment (%)	5.0	10.0	8.1
Tails assay (%)	0.3	0.3	0.3
C/HM	0	363	425
Thermal efficiency (%)	33	46	42
Natural uranium consumption (kg/MWe-day)	0.630	0.439	0.565
Separative work consumption (SWU/MWe-day)	0.397	0.321	0.399
Depleted uranium generation (kg/MWe-day)	0.575	0.420	0.535
HM mass (g/pebble)	-	10.06	9
Relative natural uranium consumption	1.00	**0.70**	0.90
Relative SWU consumption	1.00	**0.81**	1.00
Relative spent fuel volume	-	**0.56**	1.00

Uranium consumption for LEU seed / thorium blanket annular core designs is now being studied

PB-AHTR Annular Core Design Update

The current baseline UCB PB-AHTR uses a radially-zoned, annular seed/blanket core configuration

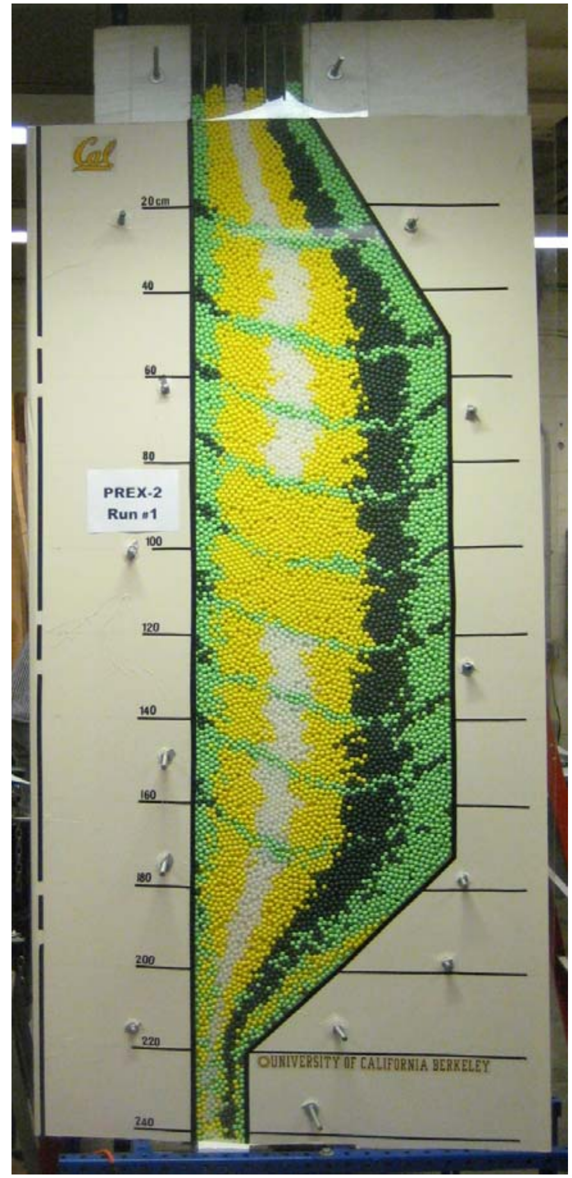
- **A PREX-2 experiment has been constructed to demonstrate the generation of a radially and axially zoned core**
- **Potential benefits:**
  - **Effective neutron shielding of outer radial reflector**
  - **Greatly reduced core pressure drop (using a combination of axial and radial flow)**
  - **Zoning allows use of thorium blanket pebbles**
    - » **External Pa-233 decay storage**
    - » **Closed and once-through seed-blanket fuel cycles being studied**



The NE170 Senior Design Class project that built PREX-3 is now a finalist for the 2009 ANS Student Design Competition

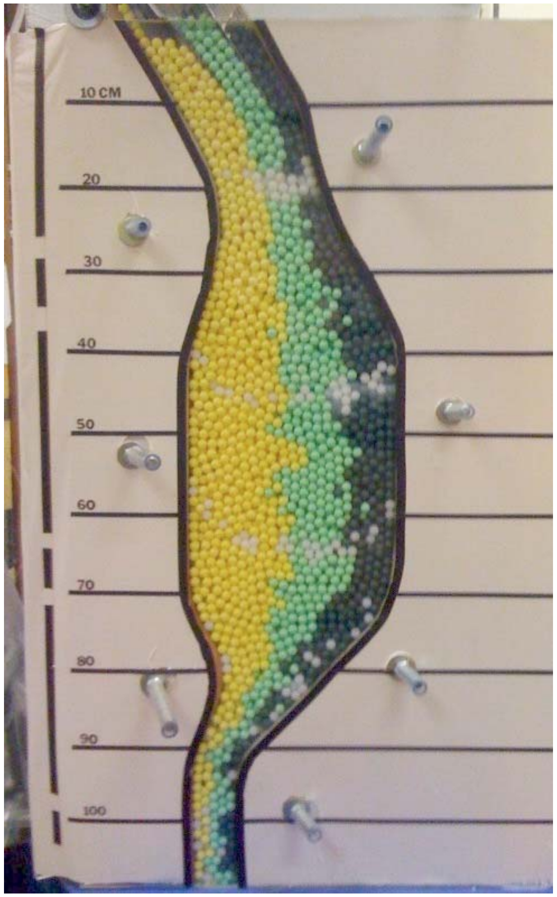
PREX-2 has confirmed radial zoning capability

- **15° sector PREX-2 experiment simulating 900-MWth annular core**
  - **129,840 colored 1.28-cm diameter HDPE pebbles in 15° sector**
  - **Average of 9460 + 1260 pebbles in each axial layer**
- **For simplicity PREX-2 is a dry experiment (unlike PREX-1), so pebbles are added to the top of the core and removed from the bottom**
  - **Hydrodynamic forces on pebbles neglected; must be studied later**



PREX-2 Run#1

PREX-3 is a dry 30° sector experiment for a FHR-16 16-MWth Test Reactor

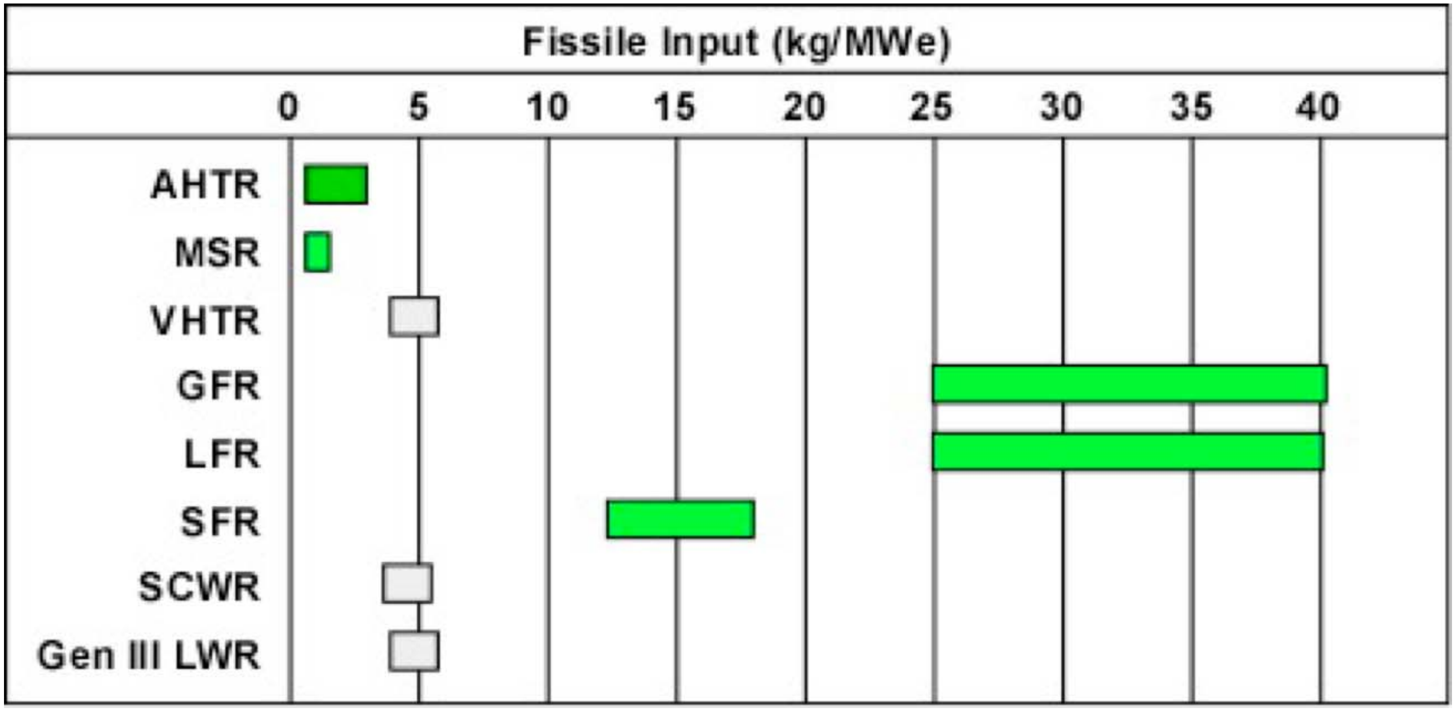


Empty **Filled**

Characteristics of AHTR seed/blanket thorium fuel cycle

- **Compatible with once-through, partially closed, and fully closed fuel cycles**
  - **Radkowski-type once-through LEU seed/thorium blanket cycle**
  - **Partially closed cycle to consume LWR TRU / excess weapons plutonium in deep-burn seed pebbles**
  - **Fully closed Th/U-233 cycle (may require substantial reprocessing or external neutron source)**
- **Uses centralized enrichment, recycle and fuel fabrication facilities**
  - **Back-end is inherently centralized due to complexity of fuel recycle and fabrication**
  - **All attractive materials (LWR TRU, U-233) handled in hot cells, making insider/outsider theft highly difficult**
- **All fresh fuel pre-irradiated in onsite reactor to be self protecting during transport to offsite reactors**
  - **Achieves same transportation security goal as co-locating modular reprocessing with reactors, without dispersing reprocessing technology/capability**

PB-AHTRs have very low start-up fissile requirements



- **Start-up fissile in seed pebbles can include U-235 in LEU, Pu-239 in recycled LWR TRU, or U-233 from recycled blanket pebbles**
  - **Most important variable for start up fissile is blanket pebble external decay storage fraction**
- **Low start up fissile requirements reduce the inertia of the global fuel cycle system**

Thorium PB-AHTR comparison to other reactors

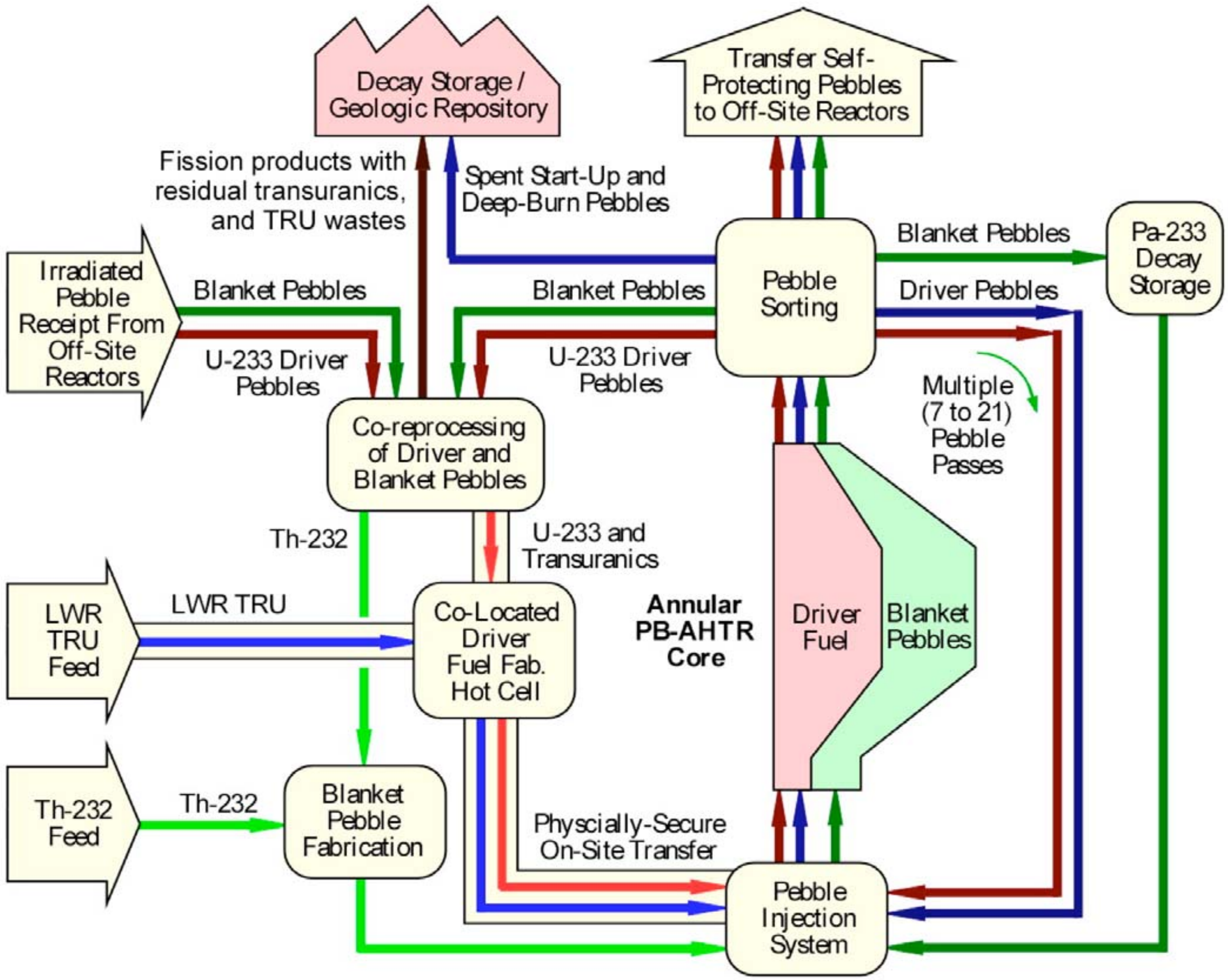
- **Comparison to Molten Salt Reactors**
  - **PB-AHTR achieves conversion ratio approaching 1 without Pa-233 chemical separation (high burnup requires operation with CR<1)**
  - **PB-AHTR has similar low start-up fissile requirements as MSR**
    - » **~0.5 kg/MWe in core, 0-2.5 kg/MWe out of core**
    - » **Compare to 4 kg/MWe for typical LWR)**
  - **AHTRs have <u>uniquely</u> large thermal margins to fuel damage**
- **Comparison to Fast Spectrum Reactors**
  - **Much smaller start up fissile requirement (several times lower)**
  - **Much smaller inventories of transuranic elements in system (plutonium, neptunium, americium, curium)**
  - **Transmutation fuels can go to very high burn up (deep burn)**
  - **Can have centralized reprocessing <u>and</u> secure fuel transportation**
- **Comparison to Light Water Reactors**
  - **Significantly smaller uranium consumption under once-through cycle extends uranium resources**

PB-AHTRs can approach the thorium utilization of MSBRs (but no need for Pa-233 separation)

	MSBR	PB-AHTR
Online refueling	Yes	Yes(1)
Xe-135 removal	Yes	No
Pa-233 removal/decay	Yes(2)	Yes(3)
Thorium breeding blanket around core	Difficult	Yes
Radial zoning of core and blanket	No	Yes
Axial alternating seed and blanket layers	No	Yes

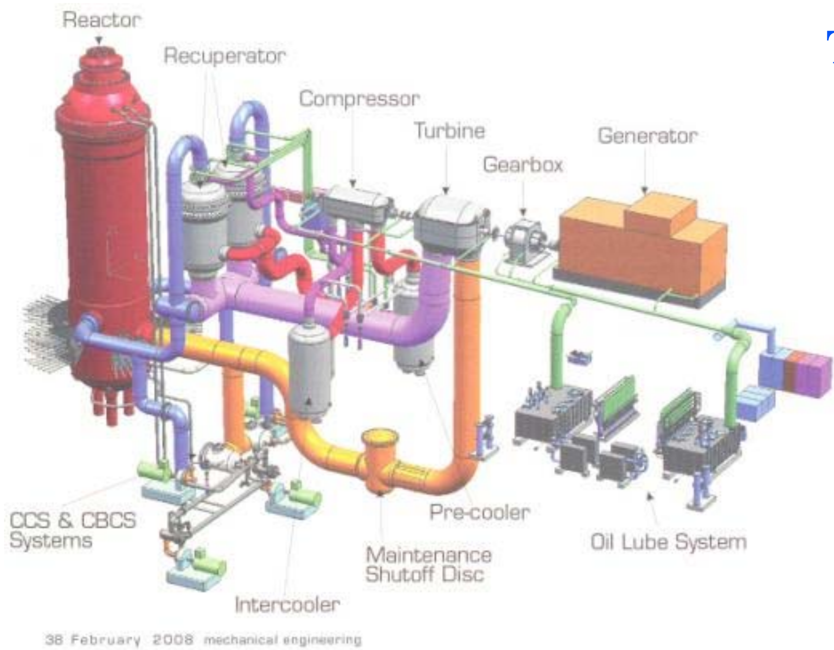
1) A small amount of excess reactivity is required to manage xenon transients. If this reactivity control is provided by removable Th-232 elements (as shown in Fig. 1), no conversion ratio penalty occurs.
2) Pa-233 management depends upon salt reprocessing rate to recover Pa-237
3) Pa-233 management depends upon blanket pebble recirculation time and external storage time.

Baseline PB-AHTR fuel cycle uses thorium seed/blanket fuel with centralized enrichment/recycle infrastructure

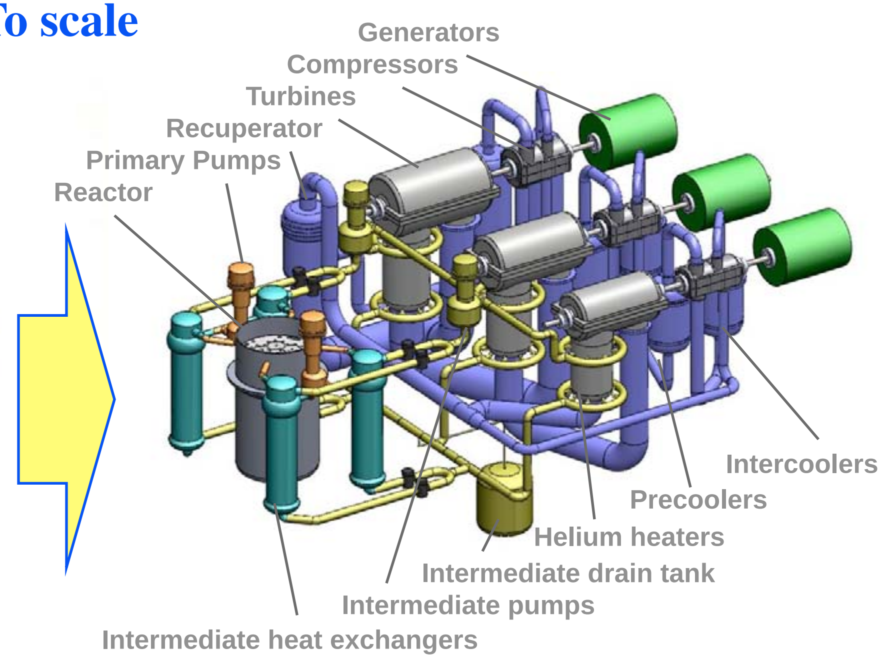


UCB Modular 410-MWe PB-AHTR Design Overview

The PB-AHTR power conversion system design is derived from the PBMR/Mitsubishi design



To scale



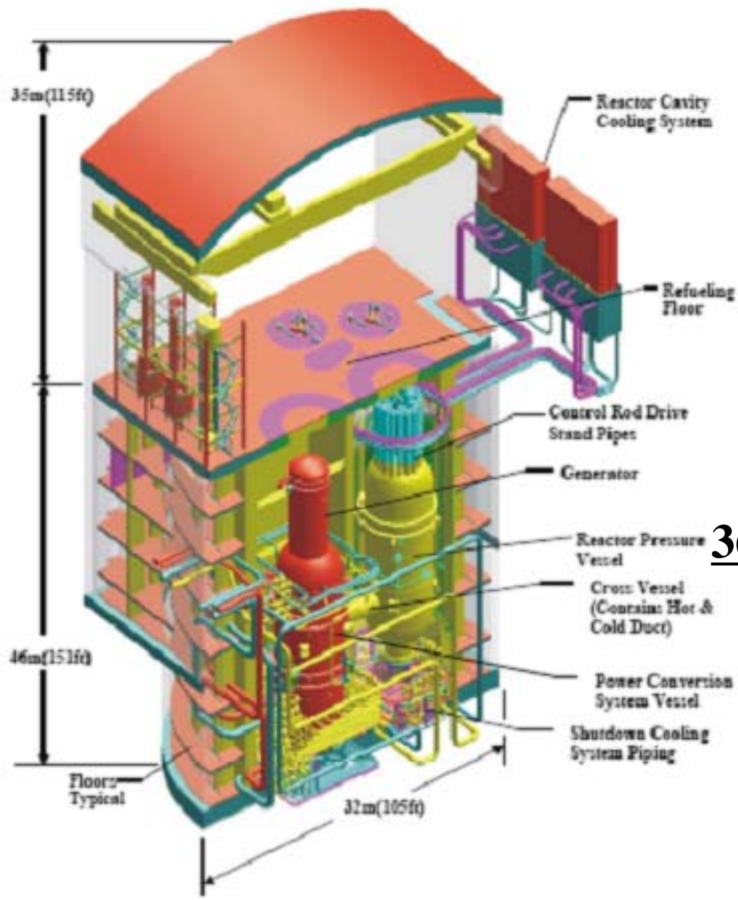
168-MWe PBMR/Mitsubishi helium cooled HTR

410-MWe PB-AHTR liquid cooled HTR

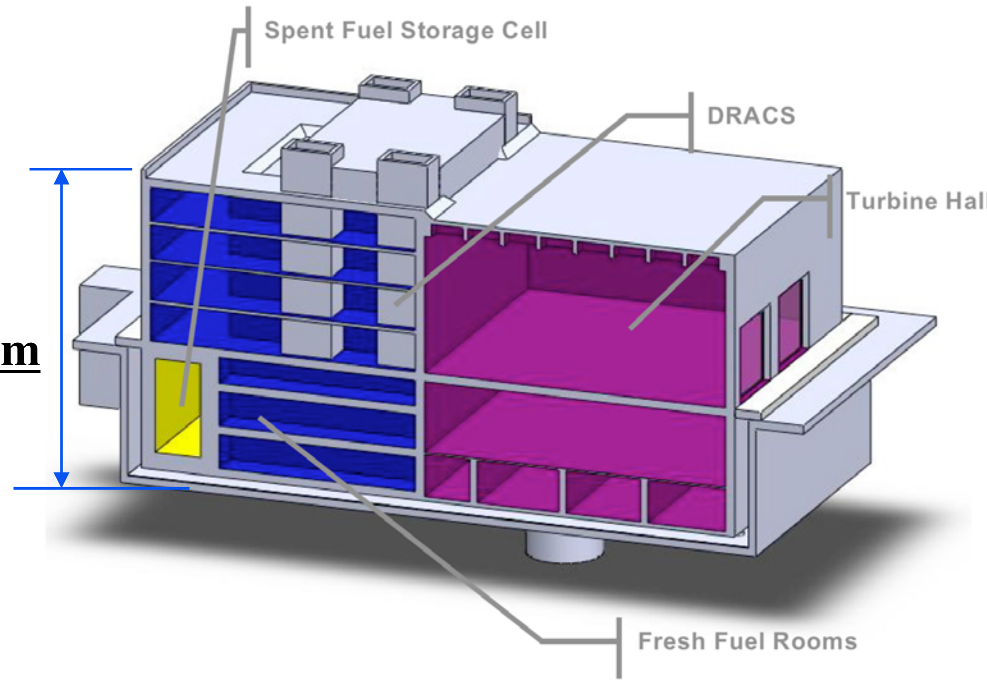
Trade study needed for multi-reheat helium Brayton vs. combined cycle vs. supercritical-CO_2

GT-MHR and PB-AHTR reactor buildings (to scale)

81m



36m



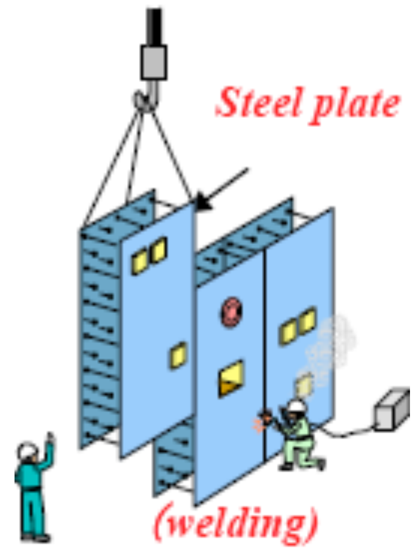
GT-MHR reactor building (287MWe)

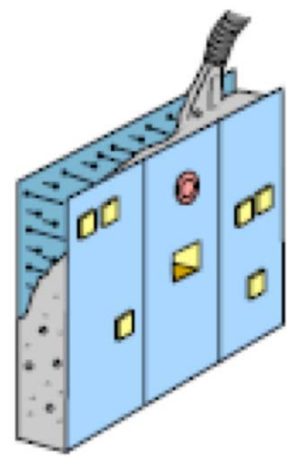
PB-AHTR reactor/turbine building (410 MWe)

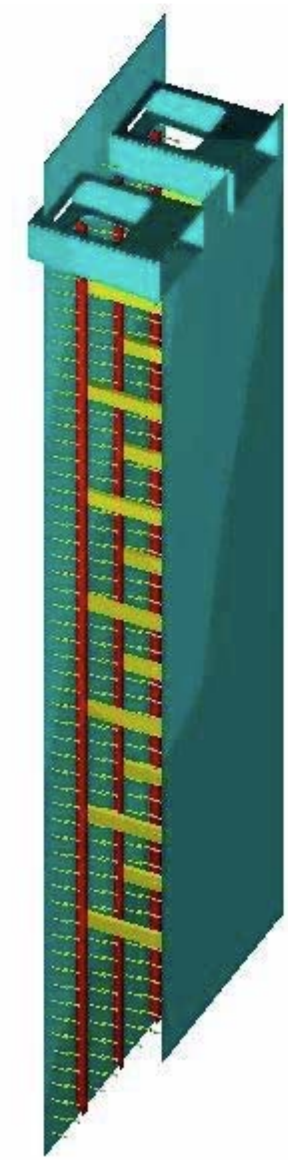
Typical LWR and SFR buildings are ~75m high

Steel-plate sandwich wall construction facilitates modular, rapid fabrication

- **Steel plate used as:**
  - Form
  - Reinforcement
- **Modular, prefabricated components**
- **Rapid construction**
  - Eliminates set up and tear down of plywood framing





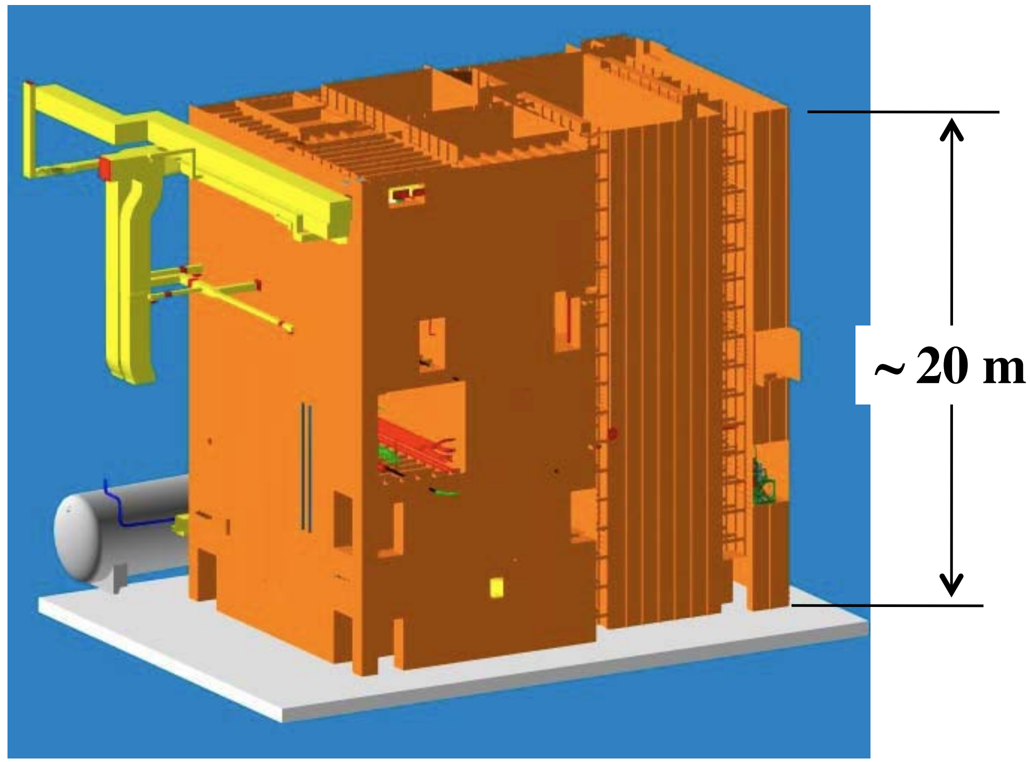


AP-1000 Structural Submodule

Steel plate reinforcement creates a more ductile reinforced structure

- **Steel plate contains failed concrete, which retains significant compressive strength**
- **Adopted by AP-1000 to upgrade containment for aircraft crash, 2-month construction schedule savings**
  - **Westinghouse has built a module fabrication factory in China capable of supplying 2 AP-1000's per year, and will open a U.S. plant at Lake Charles, LA**
- **Steel plate construction has been adopted for new plants in Korea, with estimated 10-month construction schedule savings**

PB-AHTR construction uses the same factory-prefabricated, modular steel-plate/concrete technology as the AP-1000



770-ton AP-1000 auxiliary building module, assembled from factory prefabricated plate components, being set in place onto foundation, Sanmen, China, July 2009

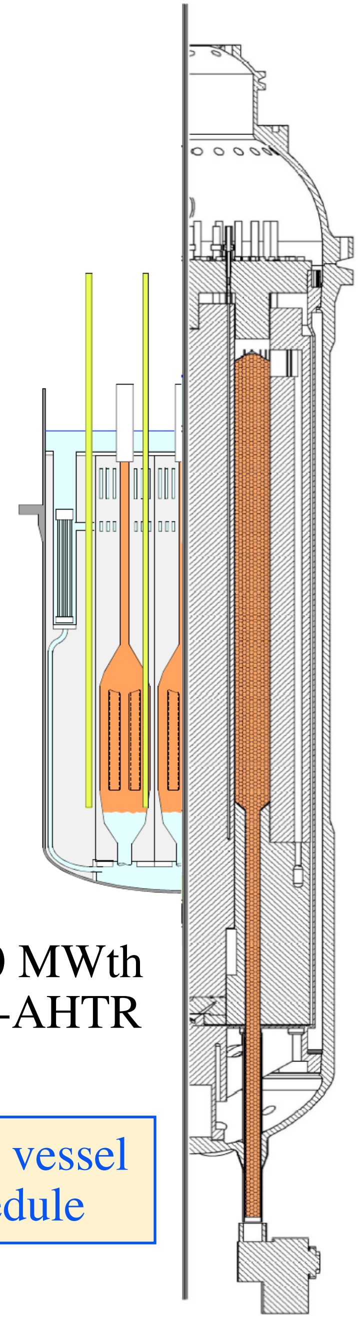
The current Modular PB-AHTR plant design is compact compared to LWRs and MHRs

Reactor Type	Reactor Power (MWe)	Reactor and Auxiliaries Volume (m^3/MWe)	Turbine Building Volume (m^3/MWe)	Ancillary Structures Volume (m^3/MWe)	Total Building Volume (m^3/MWe)
1970's PWR	1000	129	161	46	336
ABWR	1380	211	252	23	486
ESBWR	1550†	132†	166	45	343
EPR	1600	228	107	87	422
GT-MHR	286	388	0	24	412
PBMR	170	1015	0	270	1285
Modular PB-AHTR	410	105	115	40	**260**

† The ESBWR power and reactor building volume are updated values based on the Design Certification application arrangement drawings.

The new Modular PB-AHTR is designed to maintain superior economics with a modular HTR design

- **Comparison of PB-AHTR with the PBMR:**
  - **2 x power output per reactor**
  - **~30 MWth/m^3 core power density versus 4.8 MWth/m^3**
  - **large reduction in vessel size**
  - **atmospheric pressure operation**
  - **4 x reduction in spent fuel volume per unit of electricity/process steam produced**
  - **maximum fuel temperature during transients/accidents reduced from 1600°C to 1100°C**



900 MWth
PB-AHTR

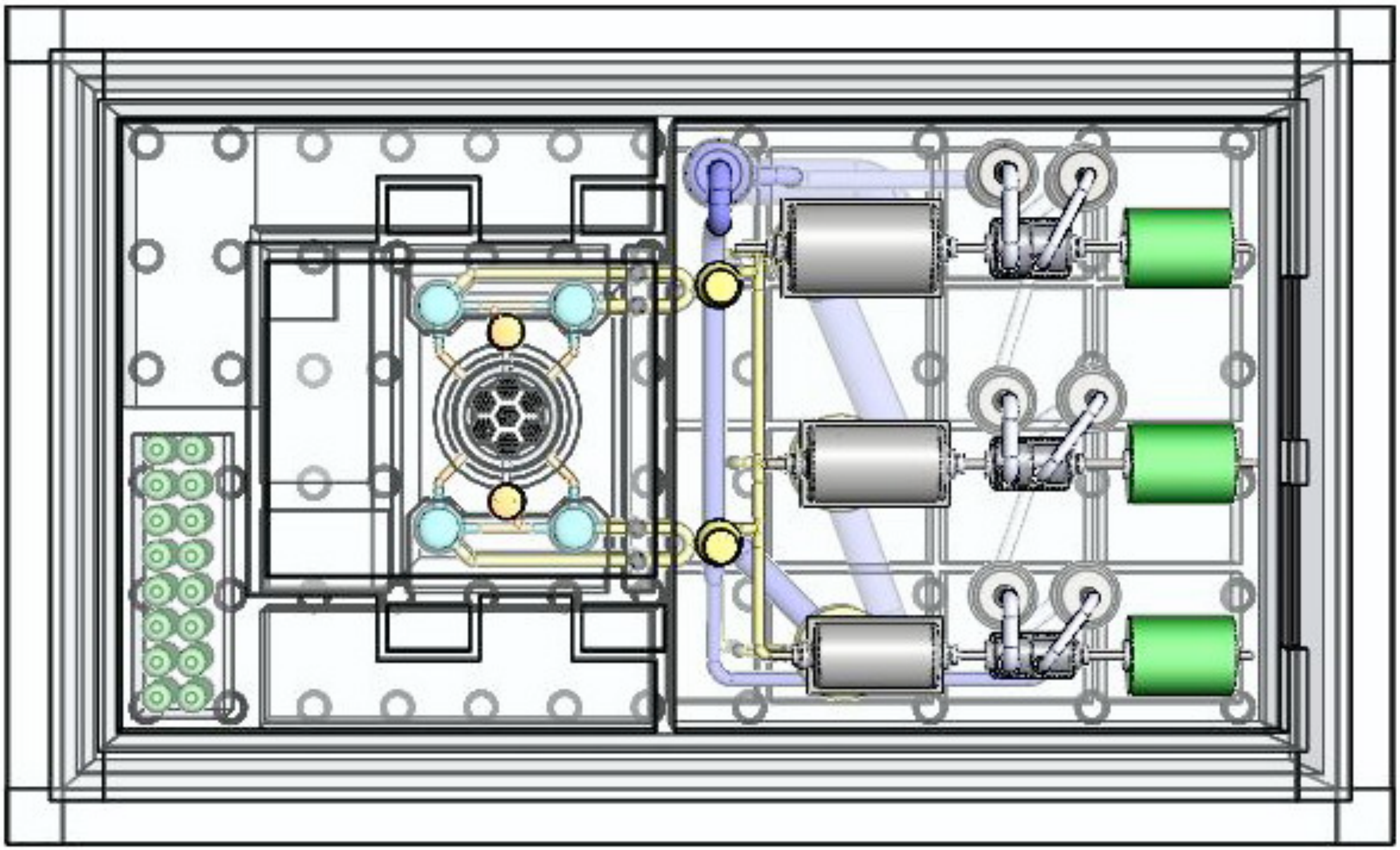
400 MWth
PBMR

The smaller size and low mass of major components (reactor vessel weight < 140 tons) has implications for the construction schedule

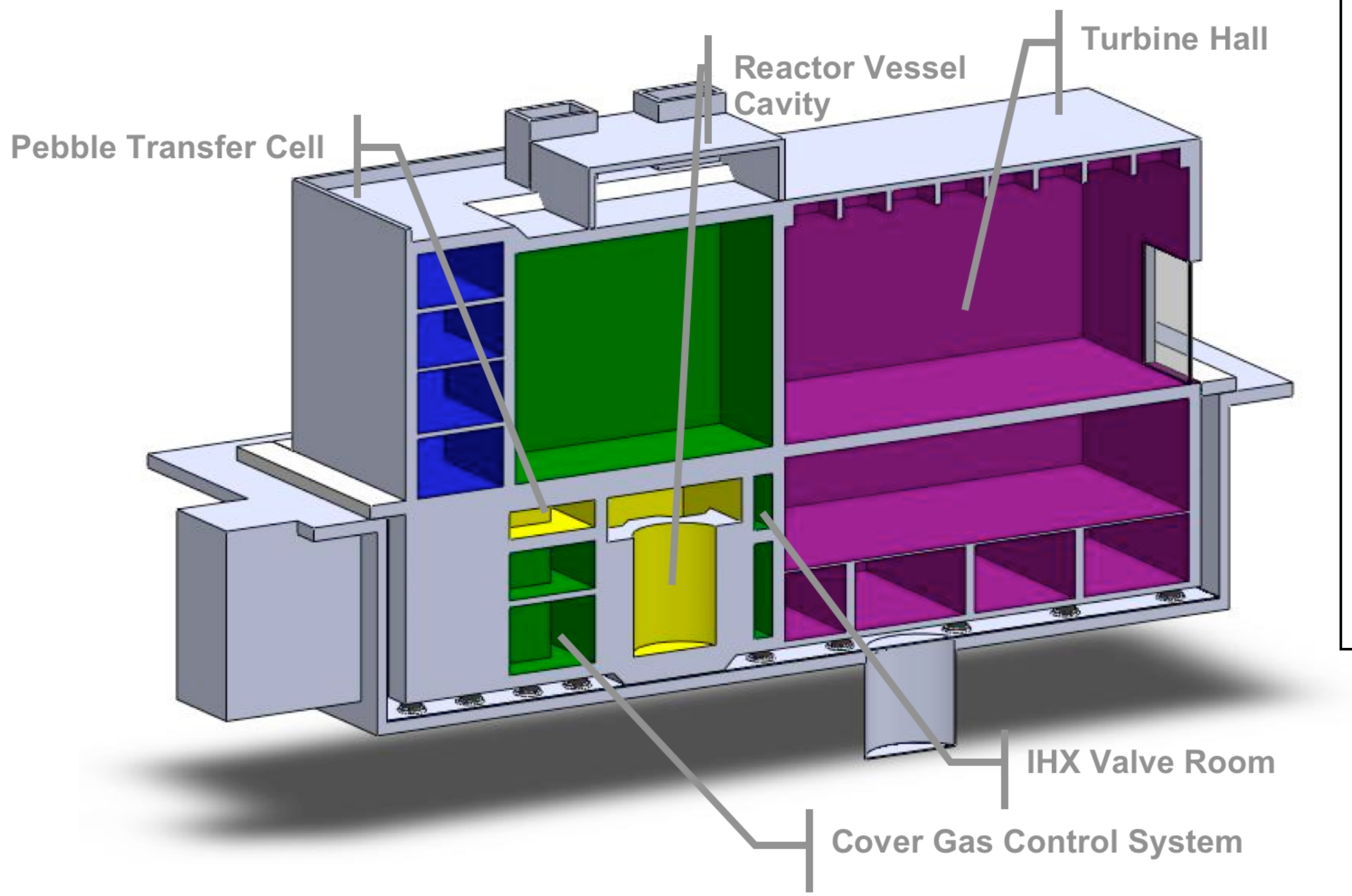
Comparison of PB-AHTR and IFR (S-PRISM)

Reactor	PB-AHTR	IFR (S-PRISM)	Ratio
Thermal Power (MWt)	900	1000	0.90
Electrical Power (MWe)	410	380	1.08
Reactor Vessel Height (m)	10.0	20.0	0.50
Reactor Vessel Diameter (m)	6.0	9.0	0.67
Reactor Vessel Volume (m^3/MWe)	0.69	3.35	0.21
External HX Volume (IHX + He heaters vs. steam generators) (m^3/MWe)	0.65	0.84	0.78

Review of major Modular PB-AHTR systems



Equipment hallways and turbine hall act as an external events shell for the PB-AHTR reactor citadel



PB-AHTR HVAC Zones

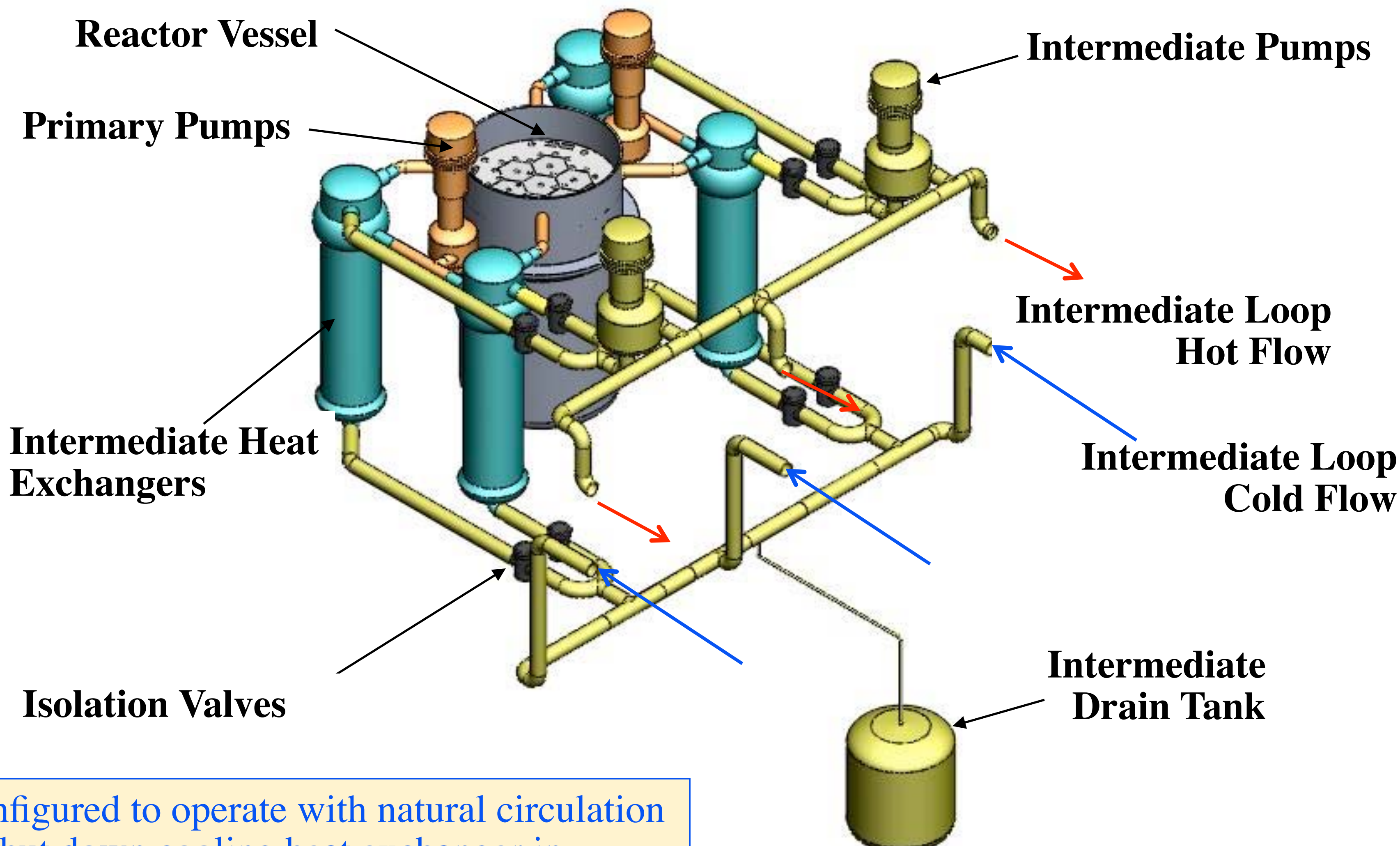
1 - Reactor cell (Low-Leakage Inerted Containment)

2 - Reactor citadel (Filtered Confinement)

3 - Reactor equipment hallways (Ambient air)

4 - Turbine hall (Ambient air)

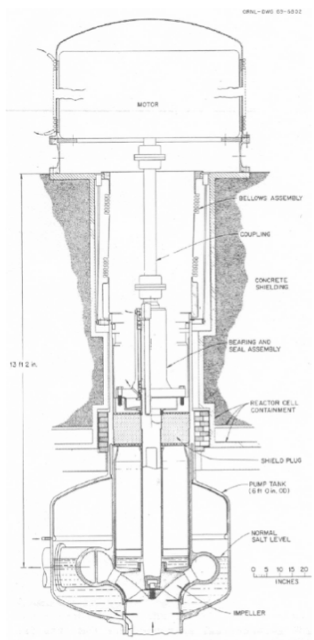
The Modular PB-AHTR primary and intermediate loops facilitate natural circulation shutdown cooling



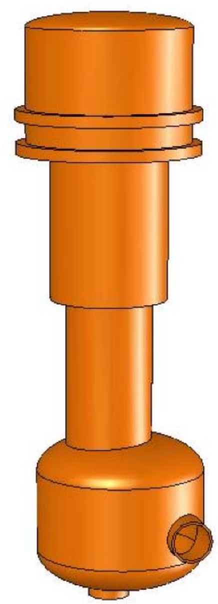
Configured to operate with natural circulation to shut down cooling heat exchanger in intermediate loop (not yet designed)

The PB-AHTR pumps use the original MSBR design

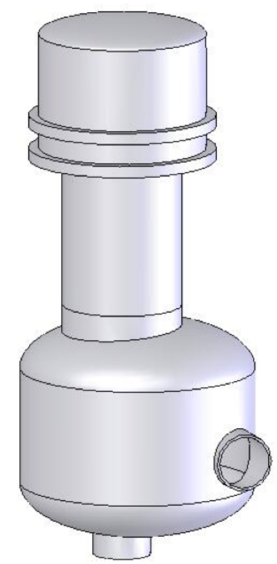
- Based on designs for the Molten Salt Breeder Reactor
- Seal bowl with cantilevered pump shaft



MSBR Salt Pump



Modular PB-AHTR Primary Salt Pump



Modular PB-AHTR Intermediate Salt Pump

The PB-AHTR IHX design is based on the MSBR

- **Counter-flow single pass vertical shell and tube heat exchanger**

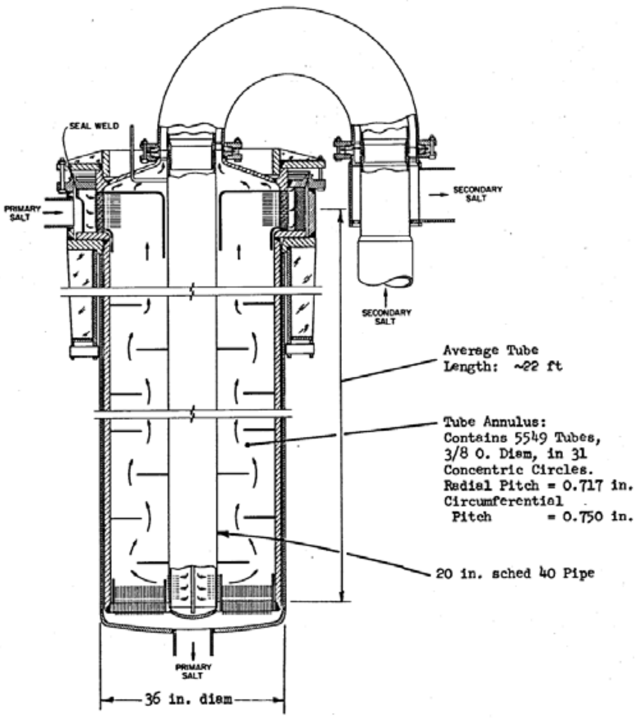
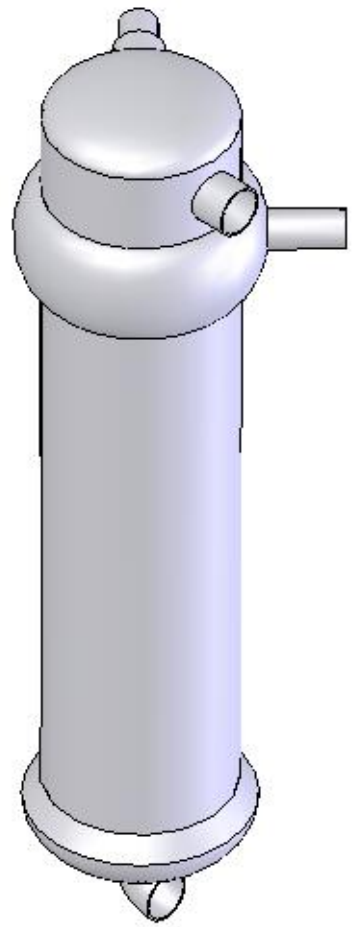
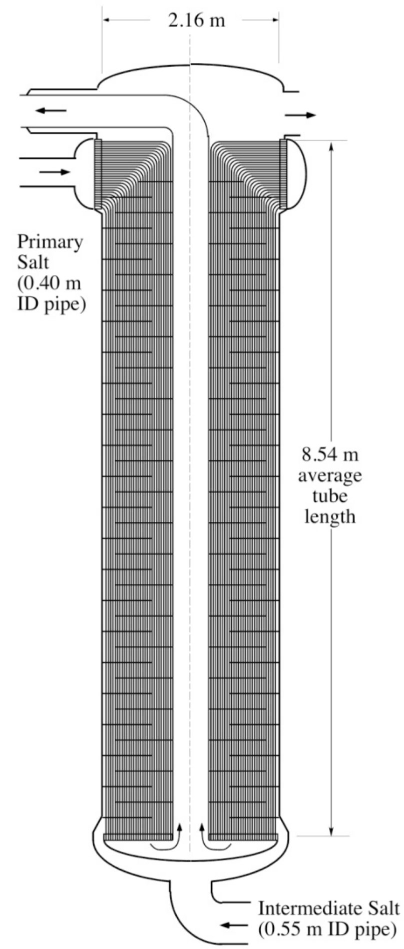


Fig. 1. MSBR 563-Mw "Reference Design" Primary Heat Exchanger.

MSBR IHX



Modular PB-AHTR IHX



Modular PB-AHTR Elevation view

Remote Maintenance

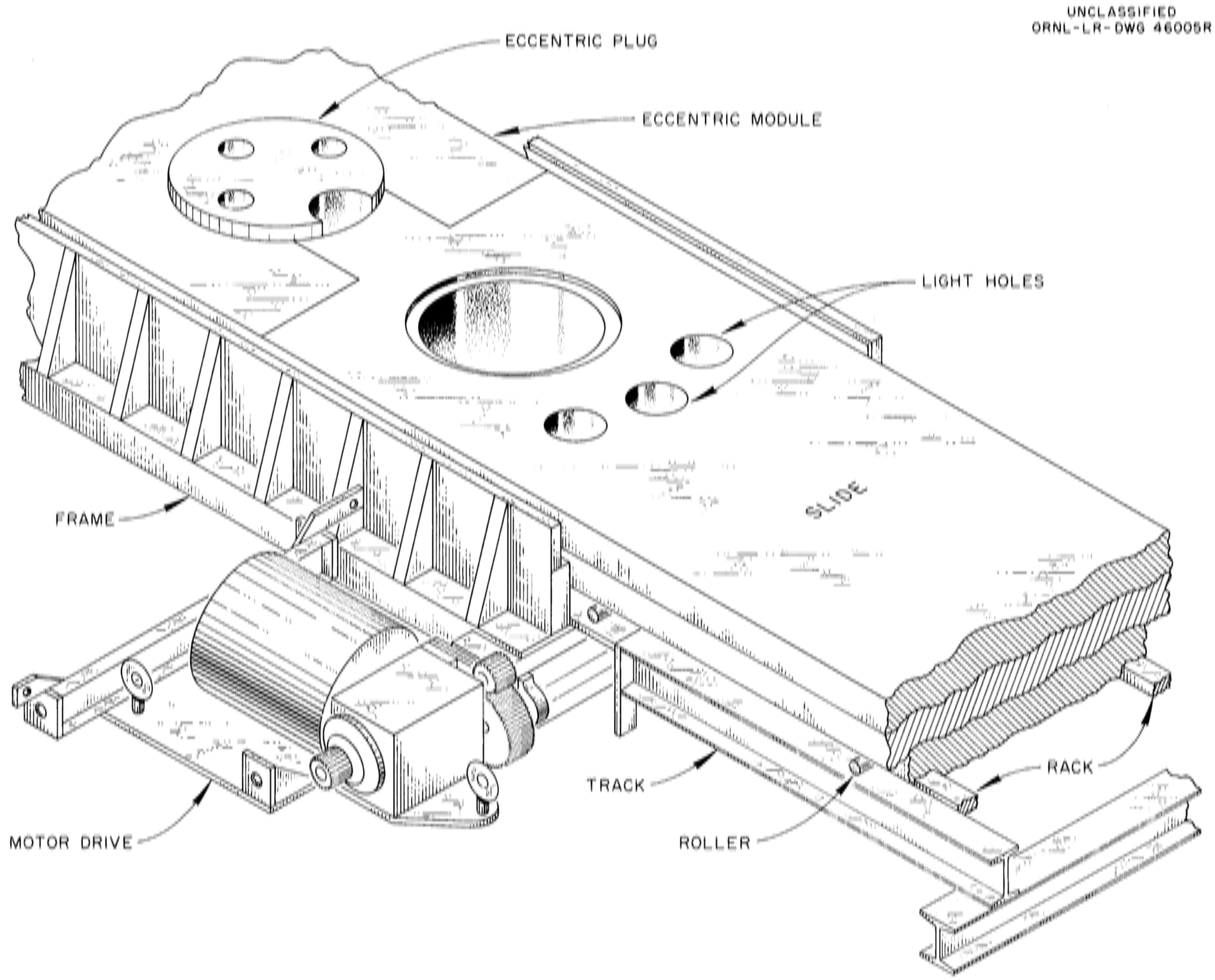
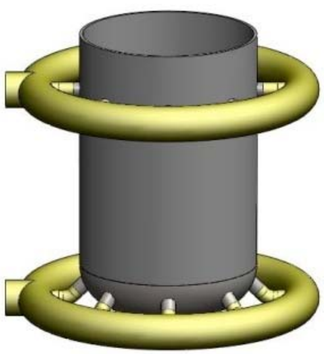


Fig. 2.14. Isometric View of Portable Maintenance Shield.

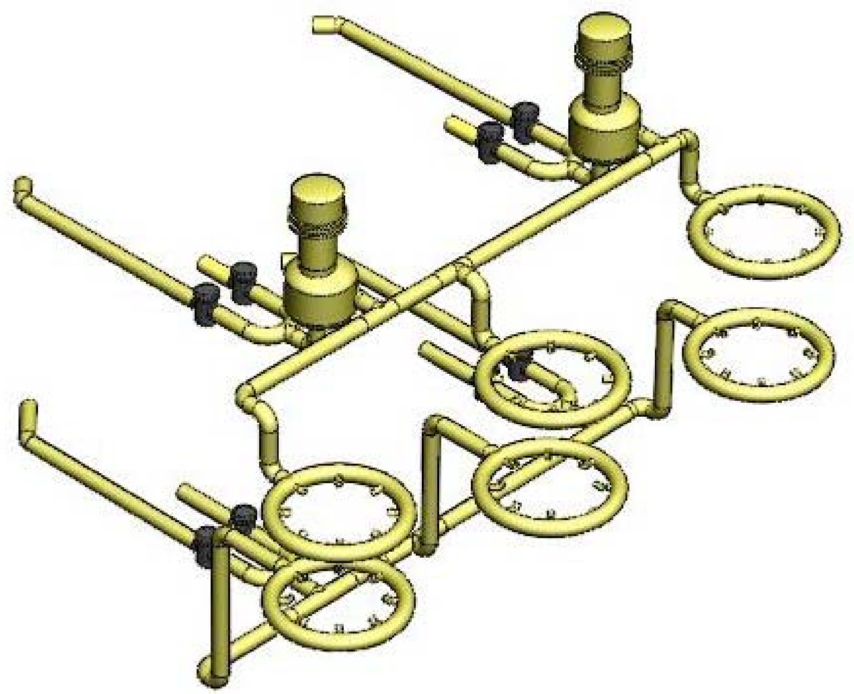
Remote Maintenance Demonstration Facility, ORNL-3122, 1961, pg. 41

PB-AHTR intermediate loop design

- Transfers heat from the Primary Loop to the Power Conversion System
- Configured to operate with natural circulation to shut down cooling heat exchanger (not yet designed)
- Low point allows for drain tank
- No beryllium (flinak)

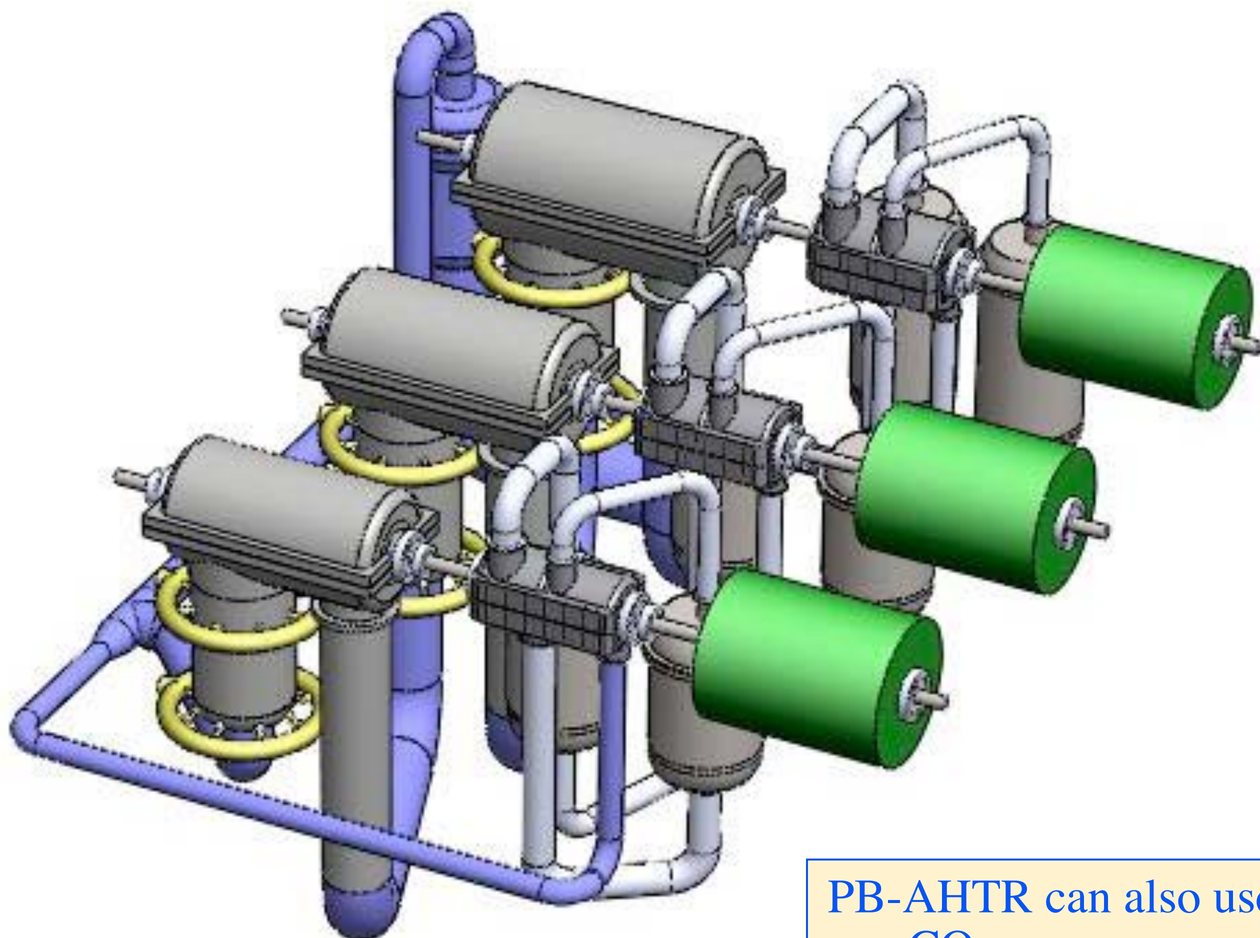


PB-AHTR Helium Heater Vessel and Feeder Rings



PB-AHTR Intermediate Loop

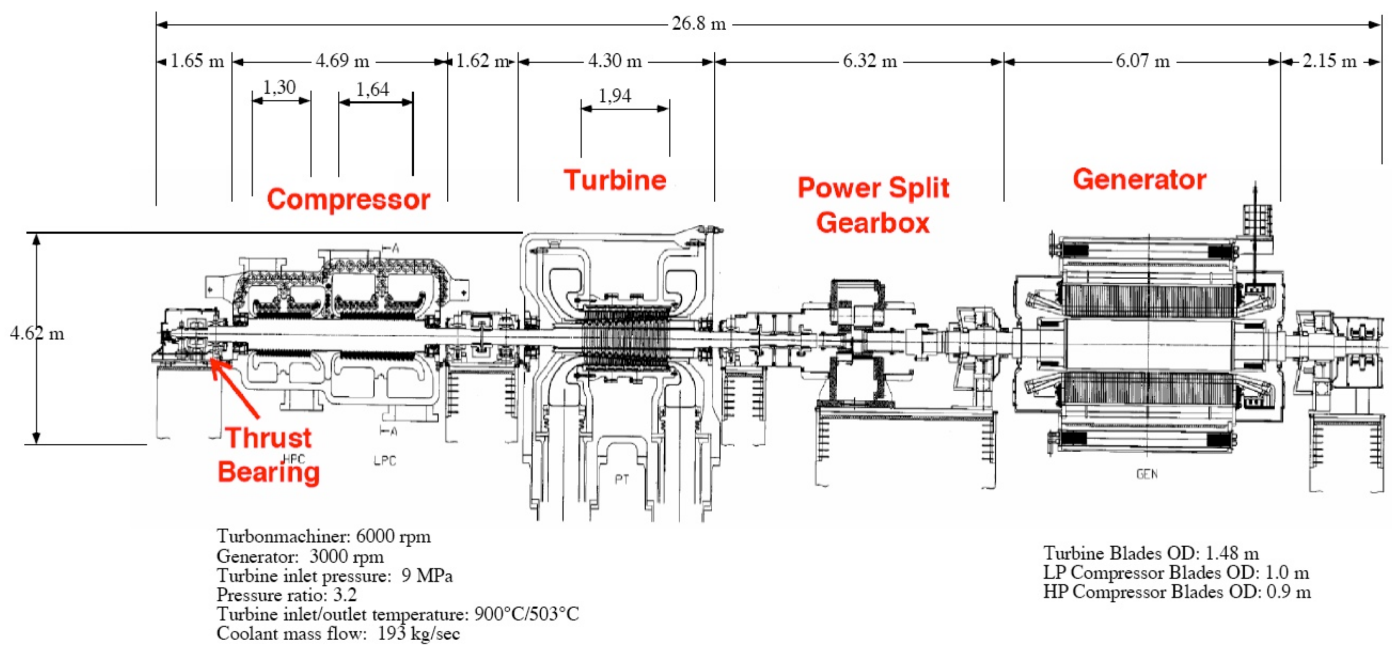
PB-AHTR 410-MWe Multi-Reheat Helium Brayton Power Conversion System



PB-AHTR can also use a supercritical CO_2 power conversion system

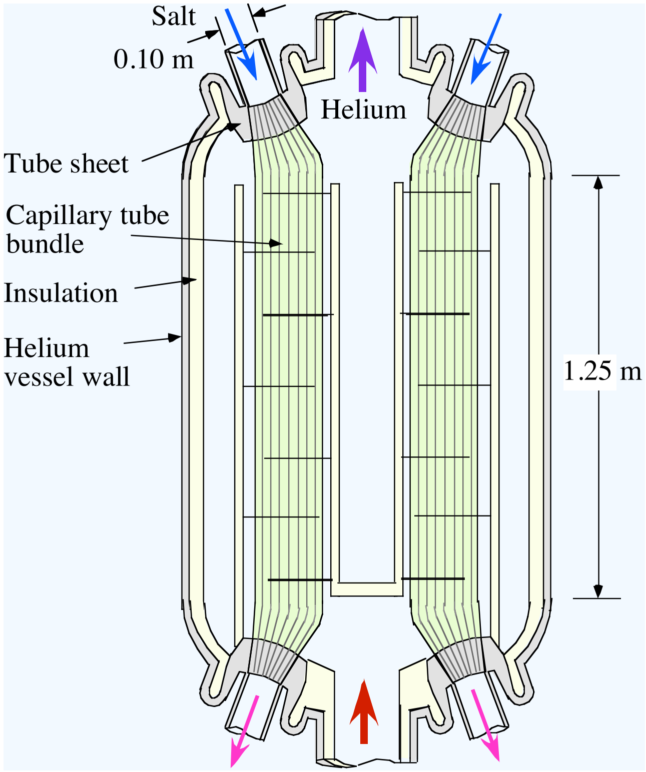
The PB-AHTR power conversion system is derived from the Mitsubishi PBMR design

- **Conventional horizontal turbomachinery with dry gas seals and oil lubricated bearings**
- **410 MWe PB-AHTR uses 3 turbine expansion stages versus 1 for the 168 MWe PBMR**
- **Higher PB-AHTR mass flow rate allows operation at 3600 rpm and elimination of the gearbox.**



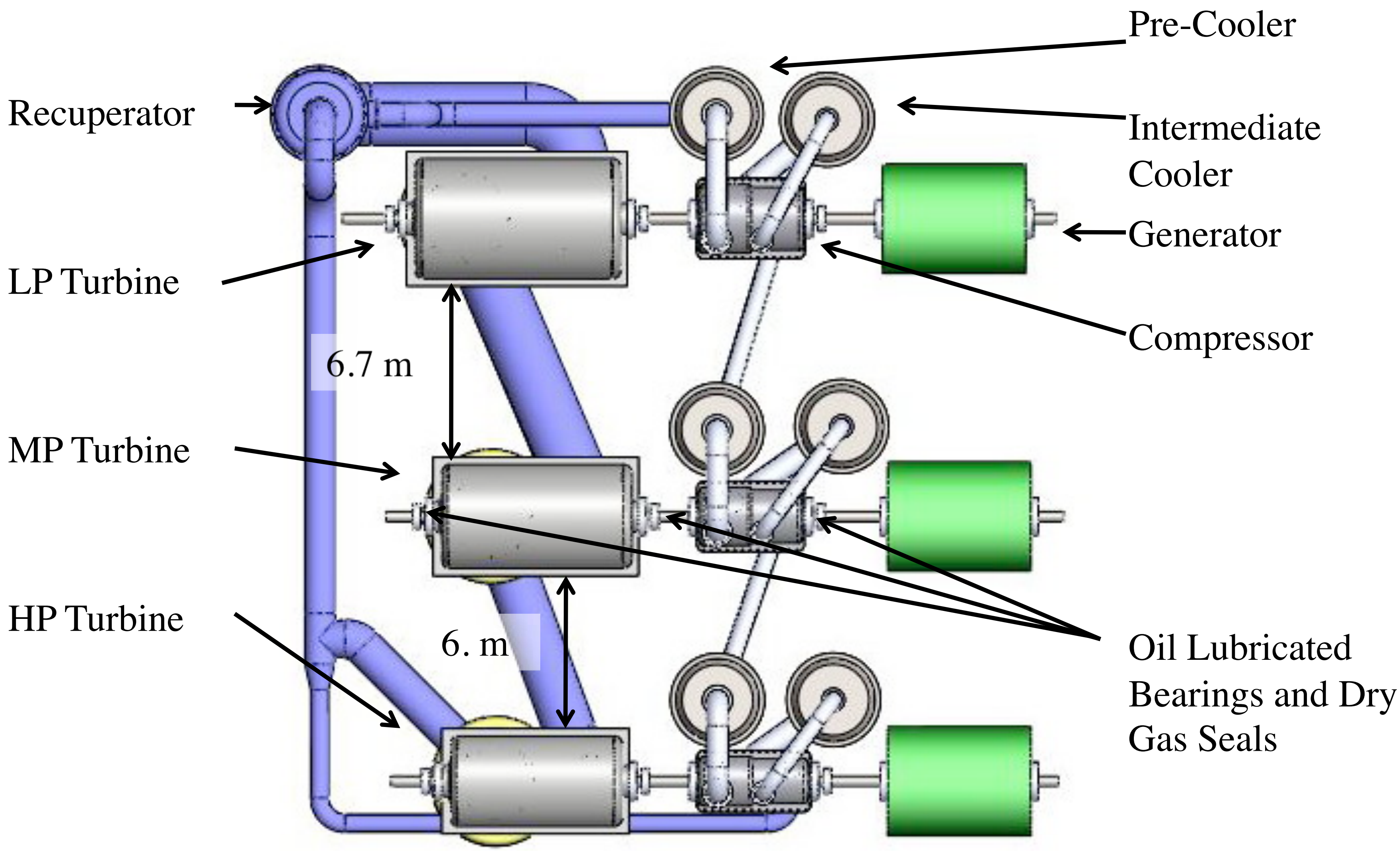
PB-AHTR requires salt-to-helium (or S-CO_2) heat exchangers

Heatric is the baseline for UCB IHX transient thermal modeling effort



UCB is collaborating with UW to develop a capillary tube and shell IHX taking advantage of low LS pumping power requirements

Components of the PB-AHTR Power Conversion System



Advanced High Temperature Reactor (AHTR)
Experimental Program

Viability phase --> Performance phase --> Demonstration phase

The AHTR Development Program has three phases

- Viability Phase
  - SET and IET experiments performed
  - Major end products are the conceptual design for a 16-MWth Test Reactor and a NRC preapplication review submittal
- Performance Phase
  - Component Test Facility operates
  - Major end products are construction authorization for a 16-MWth Test Reactor and submittal of a NRC Design Certification application for a commercial prototype
- Demonstration Phase
  - 16-MWth AHTR Test Reactor operates
  - Major end product is NRC Design Certification and a NRC Combined Construction and Operating License for a commercial-scale Pilot PB-AHTR Plant

Gen IV Viability Phase

Gen IV Performance Phase

Gen IV Demonstration Phase

The AHTR Experimental Program

- Integral Effects Tests
  - Compact Integral Effects Test (CIET) facility (Viability phase)
    - » Scaled simulant fluid IET to study system response to LOFC, ATWS, and other transients
  - Pebble Recirculation Experiment (Viability phase)
    - » Scaled simulant fluid IET to study pebble recirculation hydrodynamics
  - Czech EROS zero power critical tests (w/ salt) (Viability phase)
    - » Validate predictions for negative coolant void reactivity
- Separate Effects Tests
  - Scaled High Temperature Heat Transfer (S-HT^2) facility (Viability phase)
    - » Heat transfer coefficient measurements using simulant fluids
  - Other SET experiments (Viability/Performance phases)
    - » Pebble friction coefficients
    - » Pebble confirmatory irradiation experiments, etc.
    - » Materials corrosion test loop experiments

The AHTR Experimental Program (con’t)

- **Component Tests**
  - Various scaled component tests with simulant fluids (water) (Viability phase)
  - Component Test Facility (CTF) (Performance phase)
    - » Major non-nuclear facility to test primary, intermediate and DRACS loop components under prototypical liquid salt conditions

- **Test Reactor (Demonstration phase)**
  - nuclear fuel loading and pre-critical (zero power) testing
  - low-power (<5%) testing and operation
  - power ascension testing and operation not in excess of 100%
  - interim operation
  - maintenance and in-service inspection procedures

- **Commercial Pilot (Commercialization phase)**

SET and IET experiments with simulant fluids

The current UCB thermal hydraulics test program has 3 facilities

PREX
Pebble recirculation IET
Match Re, Fr, pebble/salt density ratio w/ water

S-HT^2
Salt heat transfer SET
Match Re, Fr, Pr, Gr w/ Dowtherm A

PRISM
Passive shutdown rod IET
Match Re, Fr, rod/salt density ratio w/ sugar water

Dowtherm heat transfer oil will be used as the principal simulant fluid for AHTR IET/SET experiments

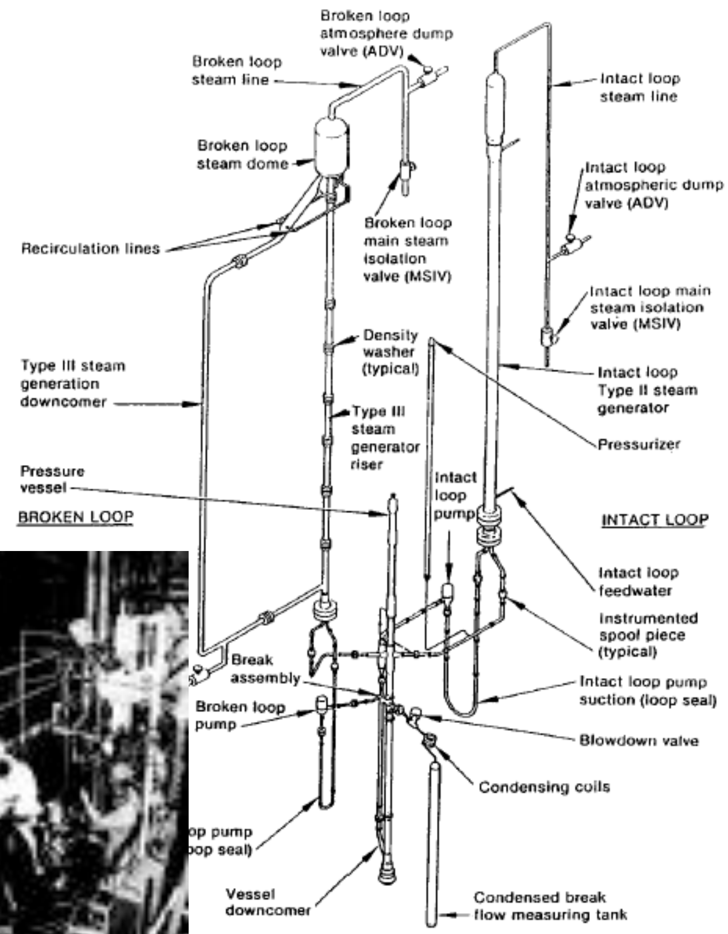
Scaling parameters to match Pr, Re, Gr, and Fr for flibe and Dowtherm A

Flibe Temperature [$^\circ C$]		600	650	700	750	800	850
Dowtherm A Temperature [$^\circ C$]		63	82	104	129	157	191
Length scale	l_m/l	0.52	0.51	0.49	0.46	0.44	0.41
Velocity scale	u_m/u	0.72	0.72	0.70	0.68	0.66	0.64
ΔT scale	$\Delta T_m/\Delta T$	0.30	0.30	0.30	0.30	0.29	0.29
Heat conductivity	λ_m/λ	0.14	0.13	0.13	0.12	0.12	0.11
Ther. diffusivity	α_m/α	0.37	0.35	0.33	0.31	0.28	0.26
$\beta\Delta T$	$(\beta\Delta T)_m/\beta\Delta T$	1.00	1.00	1.00	1.00	1.00	1.00
$\gamma\Delta T$	$(\gamma\Delta T)_m/\gamma\Delta T$	0.81	0.94	1.06	1.13	1.13	1.04
$\kappa\Delta T$	$(\kappa\Delta T)_m/\kappa\Delta T$	-0.84	-0.86	-0.89	-0.92	-0.95	-0.99
Pumping power	$P_{p,m}/P_p$	5.2%	5.0%	4.2%	3.4%	2.8%	2.1%
Heating power	$P_{q,m}/P_q$	2.1%	2.1%	1.9%	1.7%	1.5%	1.3%

- Note that Pr, Re, Gr and Fr can be matched at < 2% of prototypical heater power
- Water can be used for hydrodynamics experiments

The new UCB Compact Integral Effects Test (CIET) facility can be compared to the INL Semiscale facility

- **Semiscale simulation of PWR LOCA**
  - **1:1 height**
  - **1:1705 flow area**
  - **1:1705 power (2 MW)**
  - **1:1 time**
  - **prototype temperature / pressure**
- **CIET simulation of the PB-AHTR LOFC/ ATWS**
  - **1:1 effective height (1:2 actual)**
  - **1:190 effective flow area (1:756 actual)**
  - **1:190 effective power (1:9000 actual, 100 kW)**
  - **1:(2)$^{1/2}$ time**
  - **reduced temperature / pressure**
  - **reduced heat loss**
  - **small distortion from thermal radiation**



e 2.2.1 Semiscale Mod-2C. (From Ref. 2.2.2.)

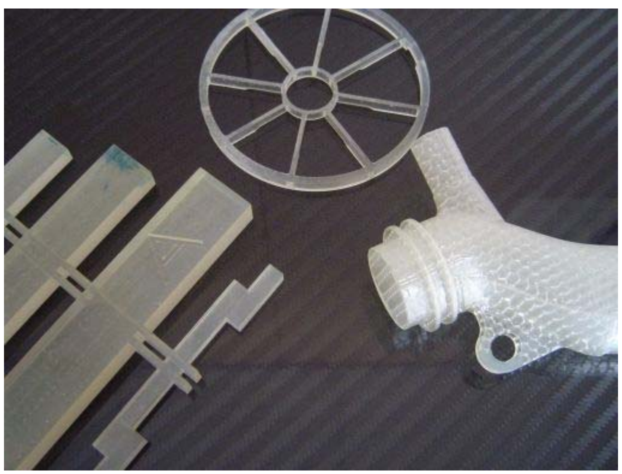
Semiscale, INL

UC Berkeley

See http://users.owt.com/smsrpm/nksafe/testfac.html for a list of other LWR IET's

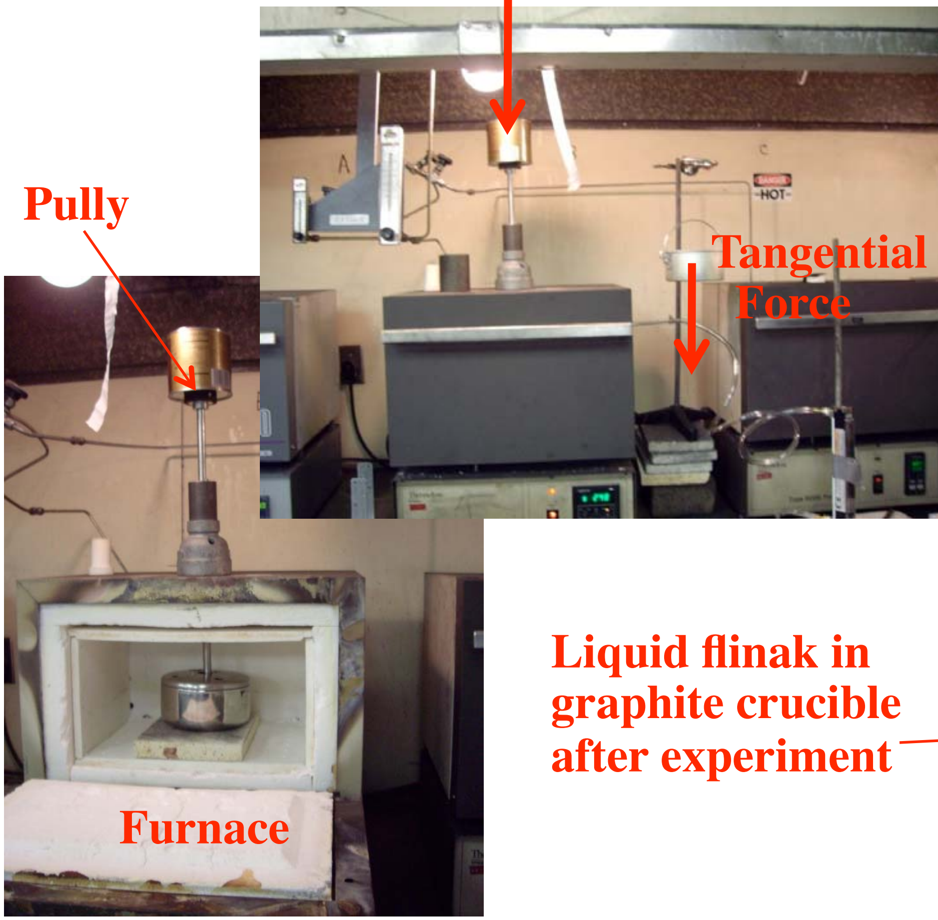
Stereolithography provides a rapid, inexpensive method to fabricate 3-D components for functional testing

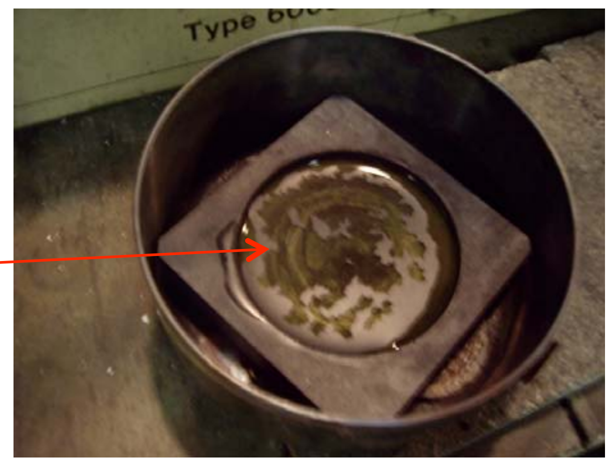
- **Can match liquid salt Re and Fr at 40% geometric scale with water**
- **Use stereolithography to fabricate and test:**
  - **Pebble defueling machine**
  - **Pebble injection machine**
  - **Fluidic diodes**
  - **Pump impellors, seal bowls (free-surface phenomena)**
  - **Valves**
  - **Complex inlet/outlet plena geometries**



Examples: SET experiments with prototypical materials/ operating conditions

Recent scoping experiments suggest that fluoride salts provide effective lubrication for graphite pebbles





Friction coefficient measurement with flinak (simulant for flibe)

UC Berkeley

Credit: Patrick Purcell, 2009 NE 170 senior design class; thank you to UW Madison for flinak

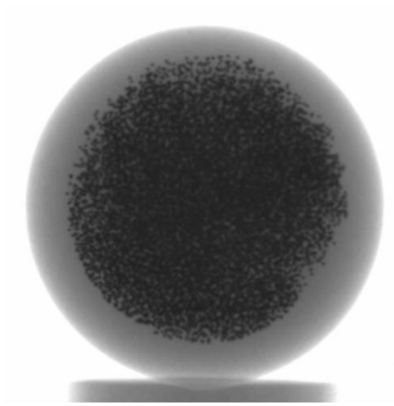
Graphite pebble friction measurement results

Temperature (°C)	Normal Mass (kg)	μ_d	μ_s
492	.915	.237	.273
	1.39	.190	.256
	1.86	.180	.253
525	.915	.224	.260
	1.39	.189	.253
	1.86	.182	.255
559	.915	.215	.251
	1.39	.187	.251
	1.86	.177	.250

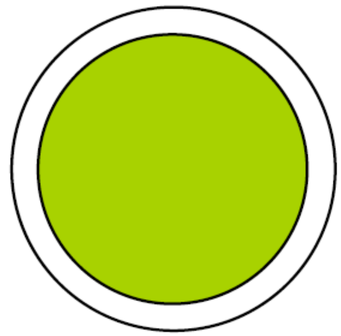
- **Friction coefficients are reduced to less than half that measured for dry helium operating conditions prior to flinak addition**
- **Compare to friction coefficient for HDPE on acrylic with water lubrication, ~0.3**

See http://www.neimagazine.com/story.asp?sectioncode=76&storyCode=2052589 for issues with friction and erosion in helium-cooled pebble bed reactors

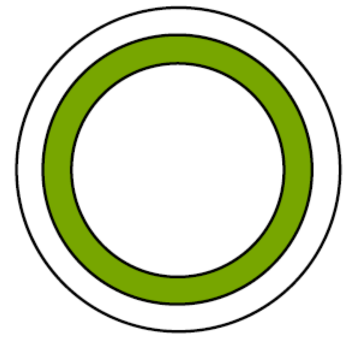
Additional SET tests will be required for PB-AHTR pebbles



X-ray image of conventional pebble



Conventional homogeneous pebble

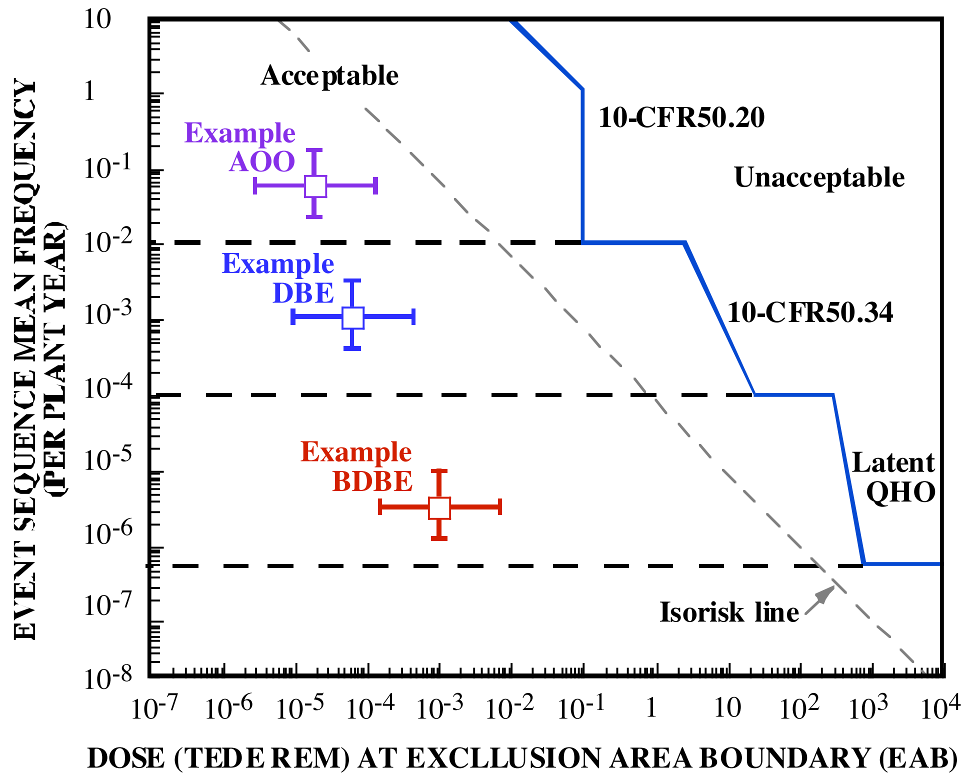


PB-AHTR "Annular" pebble

- **The PB-AHTR annular pebble configuration**
  - **Reduces maximum fuel temperature by ~140°C**
  - **Kernel density can be adjusted to set overall pebble density**
- **PB-AHTR pebbles operate at ~4-6 times higher power density that conventional pebble fuel**
  - **Accelerates fuel testing (< 1 year for seed pebbles)**
  - **But challenges peak particle power limits**
- **Technologies should be explored to "bar-code" pebbles**

The PB-AHTR licensing approach will be similar to PBMR/NGNP

AHTR safety assessment and licensing involves the systematic identification of Licensing Basis Events



Anticipated operational occurrences

Design basis events

Beyond design basis events

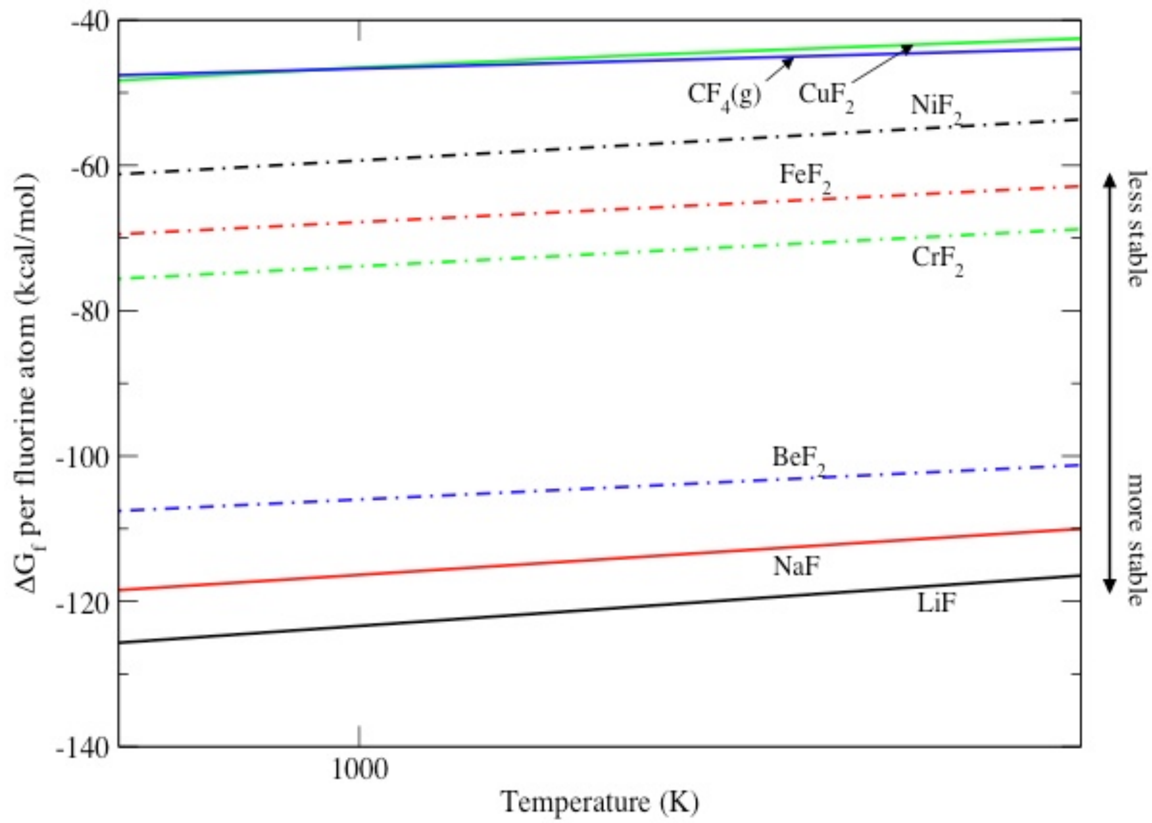
- **AHTR LBE's may be generated by internal or external events**
- **AHTR LBE's are categorized by frequency**
- **For conceptual design, LBE's for AHTR include Loss of Forced Circulation (LOFC), Loss of Heat Sink (LOHS), and Anticipated Transient Without Scram (ATWS) with LOFC or LOHS**

Component Reliability Test Program

Liquid Salt Component Test Facility

- **The role of the liquid salt Component Test Facility is to maximize the quantity and quality of reliability-related information available for applying liquid salt technologies to nuclear and non-nuclear systems.**
- **The CTF will be scaled to test components for the first AHTR Test Reactor and the subsequent commercial-scale Pilot Plant.**
- **The CTF will enable the development of high-quality probabilistic risk assessment (PRA) tools that can be used in USNRC licensing. Likewise, the CTF must demonstrate the implementation of modern design, operating, plant health monitoring, and maintenance procedures that can maximize the reliability and availability of future nuclear plants using liquid salts.**
  - **Performance-phase CTF Test Loop sized for small (16 MWth Test Reactor) components**
  - **Demonstration-phase CTF sized for commercial-scale Pilot Plant**

AHTRs use reduced salt conditions to maintain very low solubility for structural materials



- **AHTR's can use a corrosion resistant cladding (Hastelloy N or similar) with an ASME Section III code qualified structural material (e.g., Alloy 800H)**
- **Highly reduced conditions maintained by contacting salt with Be metal**

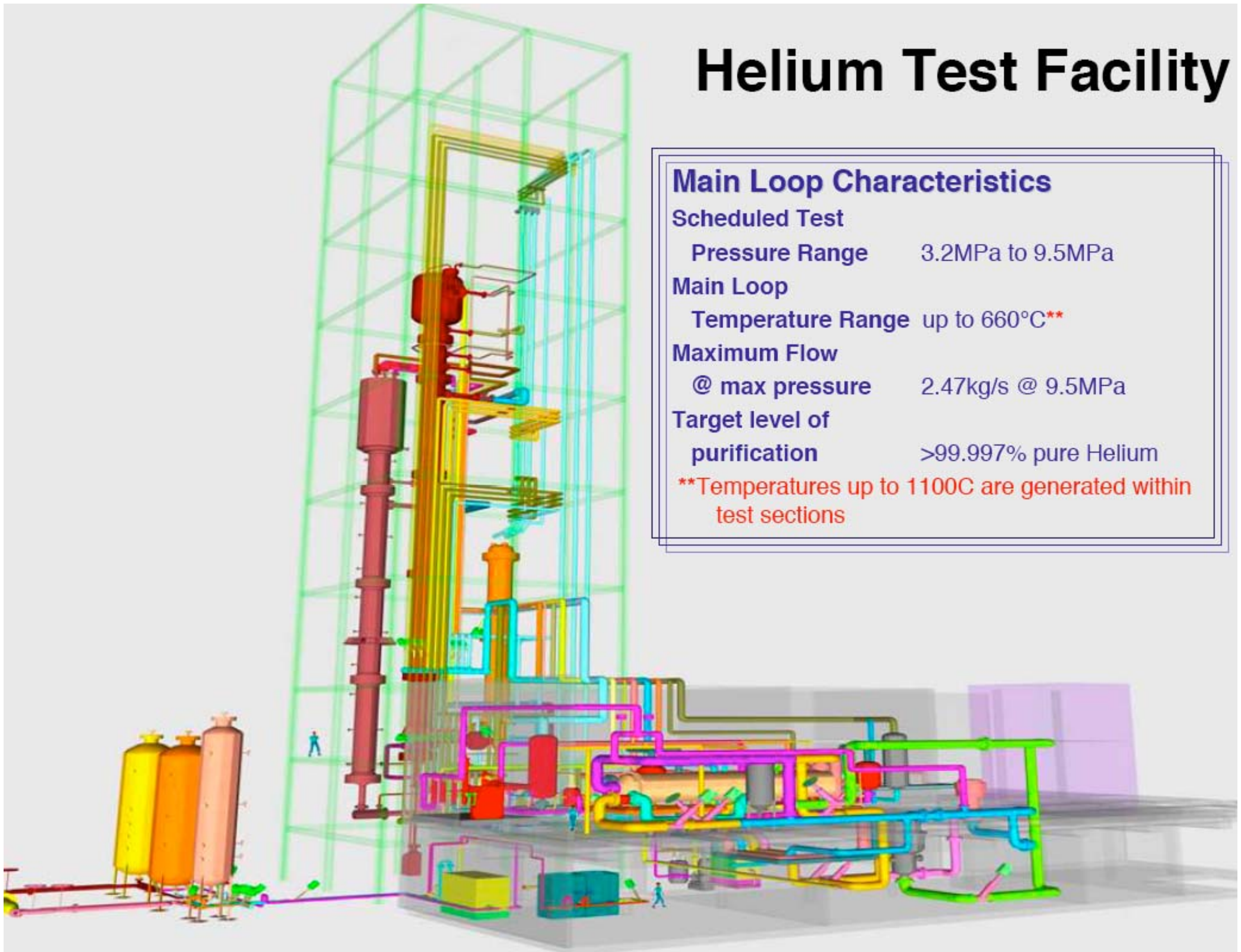
The Component Test Facility (CTF) will confirm operational reliability and maintenance methods for PB-AHTR components during Performance and Demonstration Phase RD&D

- **The CTF is a non-nuclear test facility generating prototypical salt conditions, to test the following Systems, Structures, and Components (SSCs):**
  - **Primary/intermediate pumps (full scale Pilot Plant pumps)**
  - **Defueling and pebble injection machines, pebble transfer system, spent/fresh pebble storage canister system**
  - **Reactor vessel (isothermal)**
    - **Single pebble channel with minimum thickness reflector**
    - **Demonstrate procedures for initial heat up and salt filling, pebble fueling and defueling, PCA replacement**
  - **Control/safety rod drive assemblies, maintenance methods (heated)**
  - **Reduced area intermediate heat exchanger (heated)**
  - **DRAC heat exchangers and heat removal system (heated)**
  - **Seismic snubbers**
  - **Reactor cavity insulation and heating/cooling system**
  - **Cover gas chemistry and thermal control system**
  - **Salt chemistry monitoring and control, leak detection, and beryllium-control systems**
  - **In service inspection and on-line monitoring equipment and methods (optical, acoustic, etc.)**
  - **Temperature, pressure, flow, redox, acoustic, control and other instrumentation**

CTF role for predicting SSC reliability

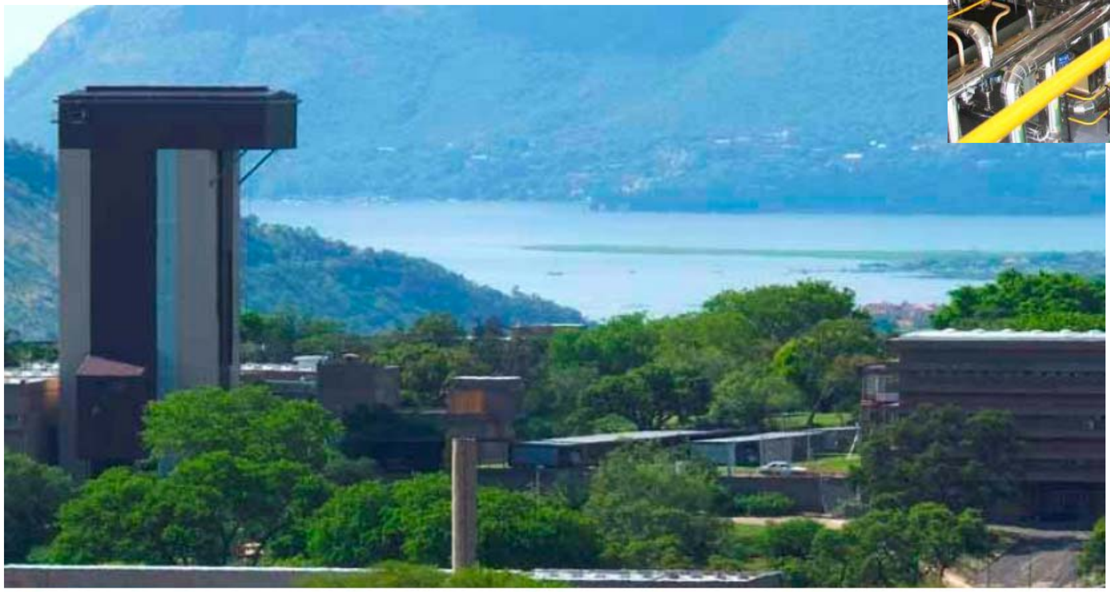
- **CTF provides reliability related data**
  - **For licensing PRA to assess frequency of internal initiating events (Q/A program will be required to use data)**
  - **For projecting reliability for financial decision making and scheduling surveillance and maintenance**
- **It is important for the CTF design and operation to be based upon modern approaches to reliability engineering**
  - **Emphasis on developing and demonstrating methods for on-line monitoring and in-service inspection**
  - **Implement an effective Corrective Action Program**
  - **PRA becomes a living tool, continuously updated with new reliability data**

The CTF performs the same major functions as the PBMR Pty. Helium Test Facility



The smaller physical size of liquid salt equipment reduces the size of a CTF

- **The PBMR HTF is a 40-m prototypical height experimental facility, that tests very large and bulky equipment**
- **Liquid salt uses small, thin-walled, low pressure components**
- **Creates implications for schedule and cost**

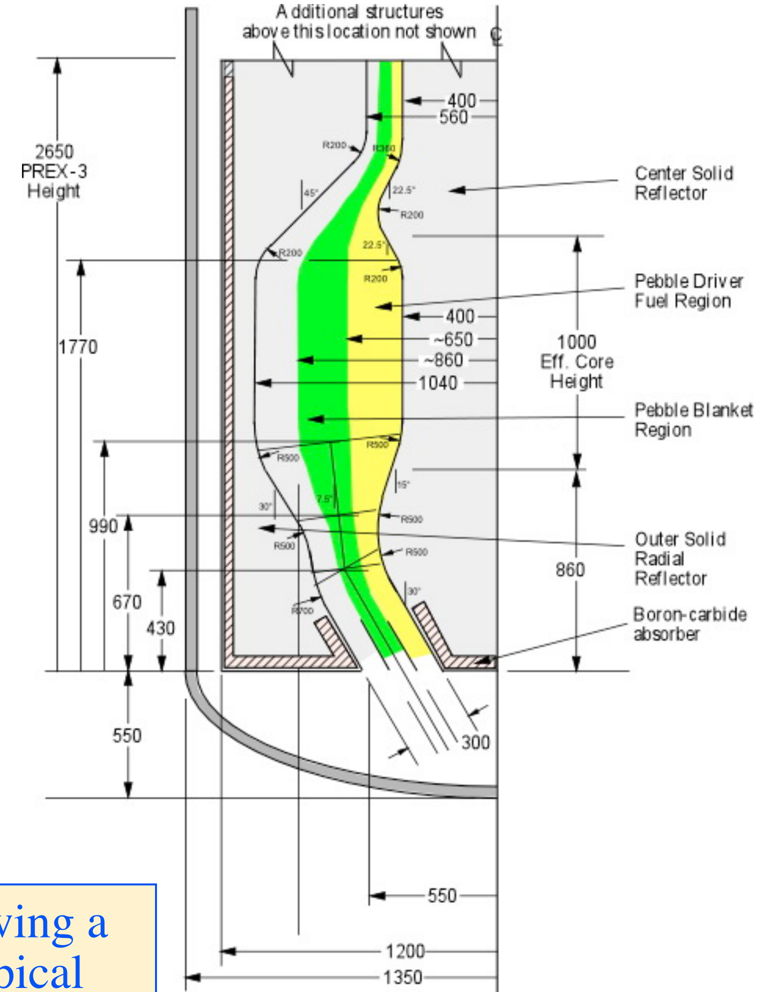


PBMR Helium Test Facility (HTF) in Pelindaba, SA

FHR-16 Test Reactor

FHR-16 is a preconceptual Fluoride-Cooled High Temperature Reactor (FHR) Test Reactor design

- **The fluoride-cooled high-temperature reactor (FHR-16) is a 16- MWth test reactor**
  - **Preconceptual design**
  - **< 20 MWth enables simplified DOE authorization process**
- **Scaled to reproduce key attributes of commercial scale plants**
  - **Inlet/outlet temperature**
  - **Peak power density**
  - **Transient response of DRACS to LOFC**
  - **Coolant chemistry control**



FHR power scaling is similar to LWRs, allowing a small test reactor to reproduce near-prototypical commercial-scale operating conditions

Potential CTF-TL/FHR-16 design parameters

- **Size Performance-Phase CFT Test Loop (CFT-TL) for flow equivalent to**
  - **16-MWth Test Reactor components**
  - **600°C inlet, 704°C outlet temperatures (but isothermal in CFT-PL)**
  - **CTF-TL substitutes flinak for flibe**
  - **Assume pump head of 14 m, average primary loop flow velocity of 3 m/s (adjust based upon detailed Test Reactor design, with upgrade possible to Pilot Plant size)**
    - » **Volumetric flow rate: 0.033 m^3/sec (520 gpm)**
    - » **Pipe diameter: 0.083 m (3.3 in)**
    - » **Pump power (70% efficiency): 13 kW (17 Hp)**
  - **Heated side stream (0.5 to 2%, 80 kW to 320 kW)**
    - » **Test salt-to-gas heat exchanger**
    - » **Solubility driven corrosion testing**
  - **Prototype key reliability engineering/modeling methods**

CTF-TL and FHR-16 can draw heavily on ORNL 8-MWth MSRE test reactor experience

Conclusions

- **The AHTR development path includes a number of different experimental programs**
  - **Integral effects tests**
  - **Separate effects tests**
  - **Component tests (functional tests w/ water, CTF tests)**
  - **Test reactor tests**
- **The liquid salt CTF provides the primary source of data to validate reliability models for AHTR SSCs**
  - **The liquid salt CTF serves as an integral effects test for SSC reliability**
  - **Design and operation should consider all elements of modern reliability engineering**
- **The ~16-MWth AHTR Test Reactor provides a fully integrated test environment for AHTR materials, systems, and fuel**
  - **Design draws heavily on experience from the 8-MWth MSRE**